RESEARCH ARTICLE

Quantitative assessment of the flow distribution in the branches of the external carotid by non-injected flow MRI

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Owing to the lack of databases of blood flow distributions in the external carotid branches, surgeons currently rely on per-operative imaging and on their experience to choose the recipient vessels for microsurgical facial reconstructions. But, thanks to three-dimensional phase contrast angiography (PCA) and kinematic CINE phase contrast (PC) sequences, MRI technologies have the potential to provide quantitative anatomical and hemodynamic information without injection of contrast agent. Having developed and optimized PC-MRI sequences for the small facial vessels, our objective was to investigate the haemodynamic and blood flow distribution in the external carotid branches. We included 31 healthy volunteers in an MRI prospective study. Two-dimensional CINE PC-MRI sequences (average duration time of 2 min 40 s $\pm$ 24 s) were performed in the external carotid collaterals ($n = 290$). A statistical analysis of the flow measurements showed that, despite large interpersonal variabilities, a general flow distribution pattern was obtained by dividing the vessel flow rates by the external carotid artery one (providing local percentages of the incoming flow). The vessels could then be classified in three haemodynamic groups ($p < 0.05$ Student's test): "low flow" group (lingual artery—12.5 $\pm$ 5% of incoming flow), "intermediate flow" group (superior thyroid artery—16.5 $\pm$ 10%, internal maxillary artery—20.5 $\pm$ 11%, superficial temporal artery—18.4 $\pm$ 6%), "high flow" group (facial artery—26.6 $\pm$ 10%). Thanks to this general flow distribution mapping, it is now possible to estimate the flow rates in the distal branches of any individual from a single blood flow measurement in the external carotid artery.

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Introduction

Microsurgical free flap is the most common method of reconstruction in the case of major head and neck defects, as it allows restoring the function while limiting aesthetic sequelae.^{1–3} But the choice of recipient vessels can be particularly complex in the case of previous surgery

or cervicofacial radiotherapy.^{4,5} In 2014, Kansy et al⁶ confirmed the lack of international consensus reporting that, in 69% of cases, the intraoperative choice was based solely on the expertise and experience of the surgeon. Despite the rapid development of imaging techniques, only Doppler ultrasound is currently used to provide qualitative and quantitative explorations of the vasculature. However, Doppler measurements⁷ face the issues of

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operator-dependency, sensitivity to bone interpositions and difficulty to guarantee finding the perpendicular plane cuts to the vessels, the branches of the external carotid artery being particularly tortuous. These limitations make their standardization difficult and reduce their reproducibility in the cervicofacial area.

MRI could offer a powerful alternative to Doppler echography to investigate the tissue morphology and haemodynamics in a same examination. Phase contrast techniques indeed allows angiography and blood flow measurement with a relatively high accuracy and without any injection of contrast agent.^{8,9}

We recently showed that it is possible to image the millimetric-sized branches of the external carotid by combining three-dimensional (3D) angiography phase contrast angiography (3D PCA) and two-dimensional (2D) CINE PC-MRI sequences (2D CINE PC-MRI).¹⁰ The protocol, which was validated *in vitro* using vessel phantoms and a mock blood flow system,¹¹ takes advantage of the fact that the face and neck vessels are superficial. It is based on the superposition of the measurements with two encoding velocities and on the use of two types of coils: a 32-element head coil and a 47 mm diameter coil to acquire accurate measurements in the smallest vessels. It, thus, accounts for the large ranges of vessel size and mean velocity that are characteristic of the face and neck vessels.

The objective of the present study was to document physiological blood flow within the branches of the external carotid artery using an original and non-invasive MRI protocol combining 3D angiography PCA and 2D CINE PC-MRI sequences.¹⁰ The secondary objectives were to determine the blood flow distribution among the branches and see how it was influenced by the anatomical geometry of the thyrolinguofacial junction.¹⁰⁻¹⁴

Methods and materials

Cohort study

31 healthy volunteers (Table 1) were included between November 2014 and August 2015. Only one healthy

volunteer was excluded following the anatomical acquisitions because of the incidental finding of a benign left parietal lesion. This study was approved by the local ethics committee (No. 2013-A00319-36), registered in clinicaltrials.gov (No. NCT 02829190), and performed in accordance with the ethical standards of the 1964 Declaration of Helsinki.

3-Tesla MRI acquisition procedures

All the acquisitions were conducted on an MRI Research PHILIPS® 3 T Achieva TX DSTREAM (Best, Netherlands). The vessel anatomy and blood flow were determined in the superior thyroid artery (STA), lingual artery (LA), facial artery (FA), internal maxillary artery (IMA) and superficial temporal artery (STempA).

At first, a 32-element head coil (Figure 1) was used to identify each of the vessels of interest by 3D PCA sequences and to position the 2D CINE PC-MRI sequences on the left and right IMA and STempAs. Then, a 47 mm diameter microscopic coil was positioned near the left and right thyrolinguofacial bifurcations (Figure 1) to acquire data in the FA, LA and STA. From the 3D PCA acquisition, we positioned a measurement plane perpendicularly to the axis of each vessel of interest and conducted 2D CINE PC-MRI acquisitions in the plane.

A plethysmograph was positioned on the finger of the volunteers to synchronize the PC MRI acquisitions with the heart rate. The resulting 16 images correspond to one entire cardiac cycle.

All the parameters of the MRI sequences are reported in Table 2. The encoding velocity V_{enc} was modified accordingly to acquire the entire range of blood velocity in the plane.

Data management software

The 2D CINE PC-MRI sequences were processed using the “Flow” software developed by Balédent et al.¹⁵ A semi-automatic active contour segmentation, based on the Vector Flow gradient algorithm,¹⁶ was performed to determine the flow curve during cardiac cycle in each artery (Figure 2). From each flow curve, the area of the vessels, average flow rate and maximum flow rate were calculated automatically by the software.

Data analysis

We recorded and calculated: (1) the mean duration of the imaging protocol to acquire the data in the five vessels of interest, (2) the blood flow distribution in the external carotid vasculature as a function of the anatomic variation type, (3) the normalized flow rates to limit inter individual variations, whereby the flow rate in each artery was normalized by the external carotid flow rate, (4) the statistical difference between the 5 values of mean flow rates, determined using a Student’s *t*-test.

Table 1 Population characteristics for the 31 healthy volunteers included in the MRI prospective study

Sex	Male:17 Female:14
Average age (years)	27 ± 7.3
Height (cm)	Male: 176 ± 12 Female: 168 ± 9
Weight (kg)	Male: 79 ± 8 Female: 61 ± 9
BMI (kg m ⁻²)	Male: 25.3 ± 2.3 Female: 21.8 ± 3.2
Cardiac frequency (beat/min)	68 ± 11
Blood pressure (mmHg)	Systolic: 13 ± 1.3 Diastolic: 8.6 ± 1.5

Table 2 Parameters of 3D PCA and 2D CINE PC-MRI sequences

	<i>3D PCA sequence</i> <i>32 head coil</i>	<i>3D PCA sequence</i> <i>47 mm coil</i>	<i>2D CINE-PC sequence</i> <i>32 head coil</i>	<i>2D Cine-PC sequence</i> <i>47 mm coil</i>
TE/TR (ms)	3/5	3/5	13/8	13/8
Spatial resolution (mm ³)	0.5 × 0.5 × 1	0.6 × 0.6 × 1.2	0.5 × 0.5 × 3	0.15 × 0.15 × 2
FOV (mm ²)	240 × 240	140 × 140	120 × 120	50 × 50
Encoding velocities (cm s ⁻¹)	30	30 and 10	between 30 and 45	between 25 and 45
Number of frames per cardiac cycle	1	1	16	16

3D PCA, three-dimensional phase contrast angiography; FOV, field of view; TE, echotime; TR, repetition time.

Results

Acquisition protocol time

The average duration of the complete protocol was 49 ± 4 min for each volunteer, which included the acquisition of the right and left vasculatures with the 3D PCA sequences (using an encoding velocity of 10 cm s^{-1} and of 30 cm s^{-1}) and of the blood flow velocities by 2D CINE PC-MRI for the five vessels of interest.

The average duration of a single 2D CINE PC-MRI sequence was $2 \text{ min } 40 \text{ s} \pm 24 \text{ s}$ depending on the cardiac frequency.

Success rates of post-processing of CINE PC-MRI acquisitions

60 external carotid arteries were studied in total, which resulted in 290 2D CINE PC-MRI acquisitions. The post-processing with the “Flow” software was successful

Figure 1 Positioning of the 2D CINE PC-MRI sequences on the 3D PCA acquisition. Two coils were used: a 32-element head coil (top box) allowing 2D CINE PC-MRI acquisitions of the Superficial Temporal Artery (STempA) and Internal Maxillary Artery (IMA); and a 47 mm diameter coil (bottom box) for the study of the thyrolinguofacial trunk: Facial Artery (FA), Lingual Artery (LA) and Superior Thyroid Artery (STA).

Figure 2 (a) 3D PCA acquisition of the external carotid vasculature, used to position the 2D CINE PC-MRI sequence perpendicularly to the vessel of interest. Insert: Determination of the vessel cross-section using a semi-automatic segmentation technique. (b–d) Time variation of the vessel cross-section, mean velocity and flow rate over one cardiac cycle. 3D PCA, three-dimensional phase contrast angiography.

in 96.7%. Among the cases of failure, we encountered 6 arteries that could be not identified on the angiographic sequences (3 STA, 1 LA and 2 STempA), and 14 vessels that could not be post-treated due to an inadequate encoding velocity or due to the presence of another vessel touching it, thus preventing its segmentation (2 STA, 1 LA, 1 FA, 2 IMA and 8 STempA).

Haemodynamic MRI analysis in a representative case

To determine the flow rate in the different arteries, 2D CINE PC-MRI sequences were analysed for each volunteer to determine the time evolution of the mean blood velocity and of the intraluminal vascular section during the cardiac cycle. The results are shown for a representative case in Figure 3. The external carotid vasculature has a separated origin for the different collateral branches of the carotid artery. To summarize the results, we hereafter provide the time-averaged, minimum and maximum values of the velocity and of the surface area, as well as the time-averaged flow rate and its corresponding value when normalized by the external carotid artery (ECA) flow rate (166 ml min^{-1}).

The percentage values with respect to the ECA flow rate make it possible to study the impact of the vascular anatomy on the external carotid flow distribution. It shows that the blood flow is very low inside the lingual

artery and that the flow rate is the highest in the facial artery.

Statistical analysis of the haemodynamics in the collateral branches of the external carotid artery database

A statistical analysis is conducted on the measurements obtained within the entire population of volunteers. The average values of mean velocity and flow rate are reported in Table 3.

The average velocities and flow rates are compared among the five arteries stemming from the external carotid artery using a Student's *t*-test: it indicates that no significant difference could be identified on the blood velocity among the five vessels ($p > 0.05$ in the Student's *t*-test). The arteries could be subdivided into three groups based on their mean flow rate ($p < 0.05$):

- (1) A “low flow rate” group, comprising the lingual artery,
- (2) A “high flow rate” group, comprising the facial artery,
- (3) An “intermediate flow rate” group composed of the superior thyroid artery, internal maxillary artery, and superficial temporal artery.

Figure 3 Haemodynamic analysis of a representative case (external carotid vasculature with separated origins for the STA, LA, FA, IMA and STempA): (a-b) 3D PCA acquisitions of the right external carotid vasculature obtained with the 32-element head coil and used to position the 2D CINE PC-MRI sequences on the (1) IMA and (2) STempA. In the red boxes, 3D PCA acquisitions obtained with the 47 mm diameter microscopic coil placed near the thyrolinguofacial bifurcations. They allow to position the 2D CINE MRI-PC sequences on the (3) (FA), (4) STA and (5) LA. (c) Flow rate, mean velocity and cross-section of the vessels during one cardiac cycle. (d) Blood flow distribution within the external carotid vasculature for the representative case: the flow rates are normalized by the incoming flow rate measured in the external carotid artery (166 ml min⁻¹). 3D PCA, three-dimensional phase contrast angiography; FA, facial artery; IMA, internal maxillary artery; LA, lingual artery; STA, superior thyroid artery; STempA, superficial temporal artery.

Furthermore, it is interesting to observe that the anatomical origin does not impact the average flow rate of the superior thyroid artery. The average flow rate being $21.3 \pm 14 \text{ ml min}^{-1}$, when it stems from the external carotid artery or from the facial artery, versus $22.3 \pm 14 \text{ ml min}^{-1}$ when it stems from the common carotid or from the carotid bifurcation ($p > 0.05$ in the Student's *t*-test).

Statistical analysis of the flow distribution in the external carotid branches as a function of the anatomical variations

The flow distribution within the external carotid branches was determined as a function of the anatomical geometry of the thyrolinguofacial junction. Figure 4 provides the values of flow rate percentages as a function of the ECA flow rate. A Student's *t*-test on the normalized flow rates provides no statistically significant difference according to the anatomy of the external carotid vasculature in the arterial flow distribution in the external carotid arteries ($p > 0.05$). It indicates that one can average the normalized flow rates over the entire population of volunteers regardless of the variation of

thyrolinguofacial bifurcation. This analysis shows that a typical distribution of the external carotid artery blood flow is: $16.6 \pm 10.7\%$ in the STA, $12.5 \pm 5.1\%$ in the LA, $26.7 \pm 10.7\%$ in the FA, $20.6 \pm 11\%$ in the IMA and $18.4 \pm 6.7\%$ in the STempA.

Discussion

The present study confirms the feasibility of a non-invasive qualitative and quantitative analysis of vascular structures using PC-MRI. We acquired a comprehensive database of physiological blood flow distribution within the vasculature stemming from the external carotid artery, which proves that flow MRI provides an operator-independent and reproducible technique to image the head and neck vessels despite the anatomic constraints encountered in this area (vascular tortuosity, bone interposition and anatomical variation).

A statistical approach was used to conduct a study of the vessel morphometry and of the local blood flow. Regardless of the anatomical variations, the blood

Table 3 Average values of velocities and flow rates measured in the interest vessels

	STA	LA	FA	IMA	STempA
Mean velocity (mm s ⁻¹)	98.5 ± 29	70 ± 24	92 ± 26	78 ± 27	112 ± 27
Flow rate (ml min ⁻¹)	22 ± 14	15 ± 6	33 ± 13	25 ± 13	24 ± 11

FA, facial artery; IMA, internal maxillary artery; LA, lingual artery; STA, superior thyroid artery; STempA, superficial temporal artery.

Figure 4 Box plot of the average flow rate measured in the five vessels of interest that stem from the external carotid artery. A statistical analysis based on Student's *t*-test indicates that the arteries may be sorted into three groups: the FA is in the “high flow rate” group, the STA, IMA and STempA are in the “intermediate flow rate” group, the LA is in the “low flow rate” group.

vessels can be classified into 3 groups based on their hemodynamic conditions (Figure 5): the “low flow” group (LA), “high flow” group (FA) and “intermediate flow” group (IMA, STA and STempA) ($p < 0.05$ in the Student's *t*-test). The independence of the haemodynamic conditions from the vasculature morphology may be surprising for the “intermediate flow” group, in which the STA, IMA and STempA arteries may branch off from various locations depending on the anatomical variation. This can be explained by the fact that they remain of the same calibre in all cases.

In the case of free flap reconstruction, the choice of the recipient vessels is a crucial step for the success of the surgery. This choice should be made considering the specific haemodynamic characteristics in the patient vessels and not only based on the patient vessel morphology, as it is currently done. Indeed, in the case of vessel options with equal congruence, it would be preferable to favour the artery with the highest haemodynamic potential.

The present study reveals the haemodynamic potential of the superficial temporal artery. With a mean measured value of $23.7 \pm 11.4 \text{ ml min}^{-1}$, it has similar flow rate values to the IMA ($25.2 \pm 12.7 \text{ ml min}^{-1}$) and STA ($21.8 \pm 14 \text{ ml min}^{-1}$) arteries ($p > 0.05$ in the Student's *t*-test). These data confirm that connecting

onto the superficial temporal artery is a relevant choice. They, thus, validate *a posteriori* the choice that some teams made using this vessel as the recipient artery of choice for the reconstruction of the scalp, middle floor and superior part of the face.^{17–20}

Furthermore, our study reveals that, in the physiological case, the blood proportion flowing in the various branches is independent of the vascular anatomy, provided one normalises (or non-dimensionalises) the local flow rates by the flow rate in the external carotid artery (Figure 4). This could suggest that blood distribution is guided by the metabolic needs of the vascularized structures and of the angiosomes.^{21,22} One of the main hypotheses to explain the anatomicohaemodynamic independence is that the body adapts blood supply according to the metabolic needs of the vascularized tissues by varying the perfusion pressures and vascular resistance of each artery. It would, thus, be conceivable to define norms of typical flow characteristics required for each tissue (bone, muscle, skin) based on their metabolic needs, and thus to define the basic haemodynamic needs of each free flap. The pre-operative choice of recipient vessels would then be made based on anatomical criteria of congruence as well as on haemodynamic criteria limiting the risk of inadequate infusion that may

Figure 5 Quantification of the blood flow distribution for the various existing anatomical variations. The values of the flow rates are provided for the arteries of interest being non-dimensionalized by the flow rate value. FA, facial artery; IMA, internal maxillary artery; LA, lingual artery; STA, superior thyroid artery; STempA, superficial temporal artery.

explain some peripheral suffering despite the permeability of the anastomosis.

From a clinical point of view, no technique except Doppler currently allows a quantification of the flows. It may be associated with errors in the measurements of the average velocity of the blood flow, due to errors in the evaluation of the angle of attack between the vessels and the Doppler probe or in the intraluminal diameter. These errors are all the more important as the vessels of interest are small and sinuous.²³ By providing the feasibility proof that flow MRI can provide a comprehensive morphometric and haemodynamic analysis of the cervicofacial arterial infracentimetric structures during the cardiac cycle, the present study enriches the imaging armamentarium for diagnostics and exploration of the main vascular pathologies. We have shown that flow MRI can provide a personalized mapping of the blood flow distribution in the external carotid branches before head and neck microsurgical procedures. Nevertheless, with a protocol of a total duration of 49 ± 4 min, it seems essential to think of techniques to minimize the sequence duration times without loss in precision in the acquisitions facilitating the daily use of flow MRI in clinics.

The essential point of the present study is that it paves the way to the constitution of morphometric¹⁰ and hemodynamic databases of the cervicofacial vasculature in physiological and pathological situations. This study shows the perspective of a digitalization of biological data, which will be key to design *in silico* mathematical

models that will help better understand and characterize the behaviour of vascular structures and blood flow.

Conclusion

Having shown the feasibility of flow MRI measurements in a physiological situation, the study opens the perspective of qualitative and quantitative analysis of infra centimetre arterial vasculature and confirms the possibility of a non-invasive and reproducible arterial exploration in the head and neck area completely operator-independent. Flow MRI could become a technique of choice in the pre-operative assessment of patients scheduled for microsurgical reconstruction or having a pathology with vascular tropism such as osteoradionecrosis or high flow arteriovenous malformations.

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