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Characterization of carotid artery by analysis of blood-flow velocity waveforms

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***Abstract*—the aim of this study is the characterization of carotid artery by analysis of blood-flow velocity waveforms. To characterise this vessel, we have estimate its transfer function and we have calculate noninvasively pulsatile and resistance index, after and before carotid bifurcation. The blood-flow velocity waveforms measured by phase contrast magnetic resonance imaging on 20 subjects. Our results showed that the transfer function is a second order for a young subjects (22±2ans) and is a first or second order for an aged subject (>60 years) it confirms that with age the arterial rigidity increases. We demonstrated that blood-flow velocity waveform is attenuated and defaced, after carotid bifurcation because the transfer function values lower than 1, for the forth first harmonics of fast Fourier transform. We showed a high significate difference (p<0.005) between the pulsatile and the resistance indexes before and after bifurcation. Then the pulsatile index decrease and the resistance increase.**

***Keywords*—Identification, carotid artery, blood flow velocity, Transfer function, pulsatile index, resistance index.**

I. INTRODUCTION

Several studies interest to investigate flow blood velocity because it can be consider as an important tool to assess for many hemodynamics parameters that can give us idea about the cardiovascular statute. Blood flow velocity waveform can be measured by serval medical imaging modality such as Single photon emission computed tomography (SPECT) 1980 [1] ,positron emission tomography (PET) [2],Ultrasound and Doppler methods [3] and magnetic resonance imaging (MRI) [4].The SPECT and PET are inosinate imaging modality that require to injected radionuclide. However, these techniques cannot be used in the case of the critically ill patient and in the case of in follow-up controls. Ultrasound Doppler method and magnetic resonance imaging quantify noninvasively cerebral flow. These techniques are the adequate techniques to measure noninvasively the blood velocity waveform. In the present study, we interested to measure noninvasively flow velocity waveform in the carotid artery, before and after bifurcation. Then we have choice to quantify the flow through MRI with Phase contrast because, it is suited to quantify the blood flow in the arteries inside the skull. However, the carnal bones limit the precision of the Ultrasound and Doppler methods [5, 6]. Flow velocity waveform was analysed for scientific and clinical aims. In the present study, we interested to characterize the carotid artery by analysis of blood-flow velocity waveforms. The aim of this characterisation is to determine in the first time transfer function between the common and the internal carotid. In the second time, we researched to measure the resistance and the pulsatile indexes. Finally, we have interested to identify the carotid system by its transfer function module, its impulse response and its bode diagram.

The carotid system consists of an initial artery, the common carotid artery, which divides into two arteries the internal carotid artery and the external carotid artery. These two last arteries are separated from the common carotid artery by an interface of complex geometric shape: the carotid bifurcation. It is therefore a matter of characterizing these media that can be considered as preparatory linear media of finite dimensions, the constraint provided is the presence of physiological (bifurcation) and / or pathological (stenosis) reflections. Since this system is difficult to access, it requires sophisticated measurement techniques and a minimum number of measurements. We have two signals, $V_1(t)$ and $V_2(t)$. One is measured at the level of the common carotid and the other is measured at the level of the internal carotid. The flow velocities are measured by the technique of MRI with phase contrast, in vivo, within the university hospital CHU AMIENS NORD. Magnetic resonance imaging (MRI) is able to quantify noninvasively the cerebral blood flow. In particular, phase-contrast velocimetry MRI (PC-MRI) sequences can provide quantitative information about the velocities of circulating fluids in blood vessels and their blood flow and associated blood flow [7,8]. To characterize carotid dynamics, we have applied the transfer function (TF) method to the velocity curves. Usually Fourier analysis is used to study blood flow signals [9]. McDonald and Taylor introduced the general

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concepts of transfer function to describe physiological phenomena [10, 11].

TF is calculated between any two points in arterial tree, in our case we have calculated the transfer function after and before carotid bifurcation. Transfer function (TF) is an important parameter for the understanding and analysis of hemodynamics in human arterial tree. It explains the dynamic temporal relation between the input-output signals of a system. It has been applied lately in the cardiovascular domain. Several works of research studied the function of transfer in breast of the organism [12, 13]. In this study, transfer function is calculate between the common carotid (input) and the internal carotid (output).
In the aim of characterization for carotid artery, we have calculated the resistance index and the pulsatile index. The resistance index (IR) is calculated by the following equation:

$$IR = VS - VD/VS \quad (1)$$

Where
VS: maximal systolic speed
VD: minimal diastolic speed
The pulsatile index is calculated by the following equation:

$$IP = VS - VD/VM \quad (2)$$

With VM: mean temporal speed

II. Materials and Methods

A. Population:

Blood flow rates and velocities were measured in 20 subjects (10 men and 10 women): 10 volunteer controls (age between 22-25) and 10 healthy elderly subjects (51-82), with no known neurological pathology, No contraindications to the MRI have been recruited. All participants signed informed consent before participating in this study.

B. Materials :

Images were acquired on a 3T MRI machine (d Stream, Philips Healthcare, Best, Netherlands) equipped with a 32-channel head antenna. The subjects were in decubitus. The data were acquired with a PC-MRI cinematic 2D sequence, making it possible to measure speeds within a defined sensitivity range at the time of programming of the sequence: the encoding speed (± Venc). This sequence parameter is defined according to the speed of the fluid to be studied (arterial, venous or cerebrospinal fluid). It therefore requires prior knowledge of the speed of the flow to be quantified. In our case, we study the cerebral arteries (internal carotid and vertebral) and finally the Venc was fixed at 80cm / s. The cutting planes for the acquisitions were positioned perpendicularly to the direction of the blood flows so as not to underestimate the flow velocity. These cutting planes were placed at the level of the cervical C2-C3, directly on a series previously acquired during the systematic morphological evaluations.

The parameters used when acquiring images are:

- the repetition time (TR): 12 ± 2ms
- the echo time (TE): 6 ± 2ms
- the acquisition matrix: 512 * 512
- Field of view (FOV): 120 * 120 ± 20mm
- cutting thickness: 3.5 ± 1.5mm
- 30 ° tilt angle

The flux images were analyzed on a dedicated software to reconstruct the flow curves on a cardiac cycle.

After the acquisition of the flux images, they are transferred to the DICOM format by a computer for analysis. A semi-automatic software (http://www.tidam.fr/) developed in the Bioflow Image laboratory allows to calculate the flow velocities in the selected vessels. Balédent and al. Have shown that the application of their program makes it possible to reproducibly quantify (in intra and inter-observer terms) the flow and velocimetry information of the blood flows in the flux images [14]. Therefore, the analysis Flux images for the computation of the flow curves and associated parameters was realized with a flow image post-processing software developed within the Bioflow Image laboratory (Figure 1). The response of the segment travelled between the two measurement points. In fact, the identification of h (t) represents the action of the medium between the primary carotid and the internal carotid.

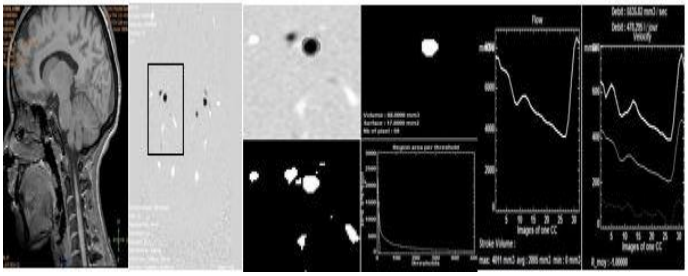

Fig. 1 segmented of internal carotid by BioFlow software

C. Methods:

Transfer function is estimated by using MATLAB System Identification Toolbox, which is presented by [15, 16, 17]. First, we load the input and output data sampling and then initialize input signal as (u) vector and output signal as (y) vectors in MATLAB workspace. After that, we open the system identification toolbox (‘ident’) and we import input and output data.

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We can represent the time domain representation, frequency to observed data; or we can estimate transfer function model.

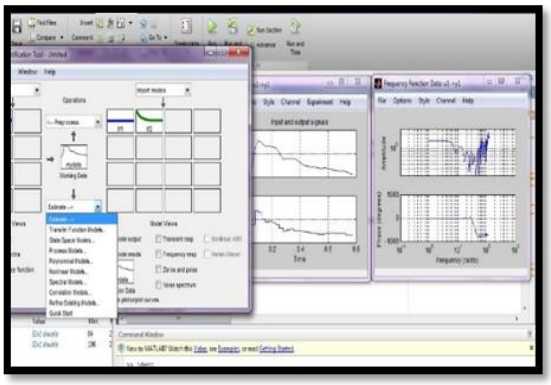

Fig. 2 Identification System (Matlab)

Based on the previous work of Baledent et al, we can also calculate the TF values by applied the fast Fourier transform and calculate the ratio between output and input for the first five harmonics [14].

$$TF = \frac{\text{amplitude } (\omega_i) \text{ out}}{\text{amplitude } (\omega_i) \text{ in}} \qquad (3)$$

Statistic test: Student t test was employed for statistical analysis. The differences were considered significant when $p<0.05$ and highly significant when $p<0.005$.

III. RESULT ET DISCUSSIONS

In this section, we present the results obtained by our study.Fig.3 shows the velocity signals at the two measuring points of the primary carotid artery and the internal carotid artery for young subjects.

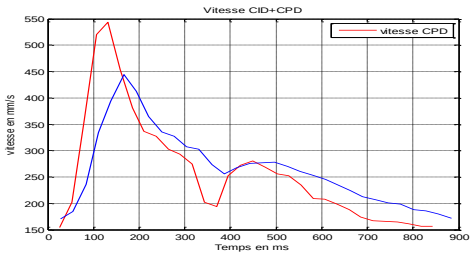

Fig. 3 The velocity waveform at the level of the primary carotid (red) and the velocity at the level of the internal carotid artery (bleu).

For a control subject, it is found that the velocity of the flow propagates from the primary carotid before the bifurcation to the internal carotid after the bifurcation with a temporal phase shift and with decrease in amplitude. To switch from the time domain to the frequency domain, we apply the fast Fourier transform. The frequency representation is shown in the following figures (fig.4 and fig.5). The spectrum of a signal is the representation of the amplitudes of different components present in this signal as a function of the frequency. When drawing the amplitude spectrum we are interested only in the amplitude and not the phase. We thus distinguish the amplitude spectrum and the phase spectrum.

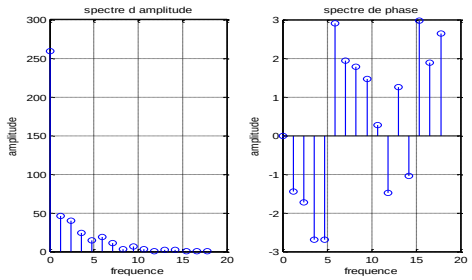

Fig. 4 amplitude spectrum (left) and phase spectrum (right) for the velocity signal at the primary carotid artery

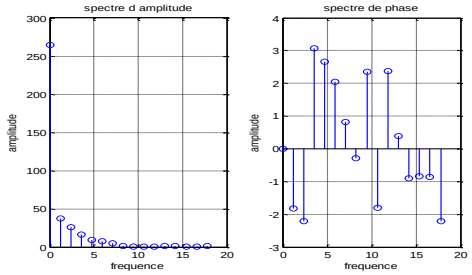

Fig. 5 amplitude spectrum (left) and phase spectrum (right) for the velocity signal at the internal carotid artery

The amplitude spectrum represents the real spectrum of the signal fork transform (TAB.1). It is formed by:
- 1st peak corresponding to the mean value of the signal.
- 2nd peak corresponding to the amplitude of the fundamental frequency

The phase spectrum is the opposite of the real spectrum. It is a complex representation of negative frequencies.

Now, we present the result obtained by Transfer function calculated for all subject (Table1). The transfer function (TF) represented attenuation when $TF<1$ and it represented amplification when $TF>1$. Figure 4 and figure 5 show the amplitude spectrums used to calculate transfer function.

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TABLE I
VALUES FOR TRANSFER FUNCTION FOR THE FIVE FIRST HARMONICS

Harmonics	1	2	3	4	5
Young subjects					
Subject 1	0.8	0.64	0.68	0.60	0.4
Subject 2	0.73	0.65	0.49	0.41	0.58
Subject 3	0.87	0.83	0.35	0.57	0.22
Subject 4	0.48	0.45	0.41	0.38	0.31
Subject 5	0.83	0.57	0.54	0.29	0.40
Old subjects					
Subject 1	0.61	0.57	0.55	0.63	0.63
Subject 2	0.51	0.44	0.5	0.55	0.44
Subject 3	0.55	0.44	0.42	0.30	0.35
Subject 4	0.89	0.81	0.66	0.71	0.63
Subject 5	0.87	0.78	0.64	0.74	0.62

- Transfer function:

Estimation de transfer function:

We demonstrated that the function of transfer is a second order for young subject and in first or second order for aged subject (fig .6):

Transfer function of a first order, 1 pole and no zero, expressed as:

$$FT_1 = \frac{b_0}{a_1 s + a_0} \qquad (4)$$

Transfer function of a second order, 2 poles and 1zero, expressed as:

$$FT_2 = \frac{b_1 s + b_0}{a_2 s^2 + a_1 s + a_0} \qquad (5)$$

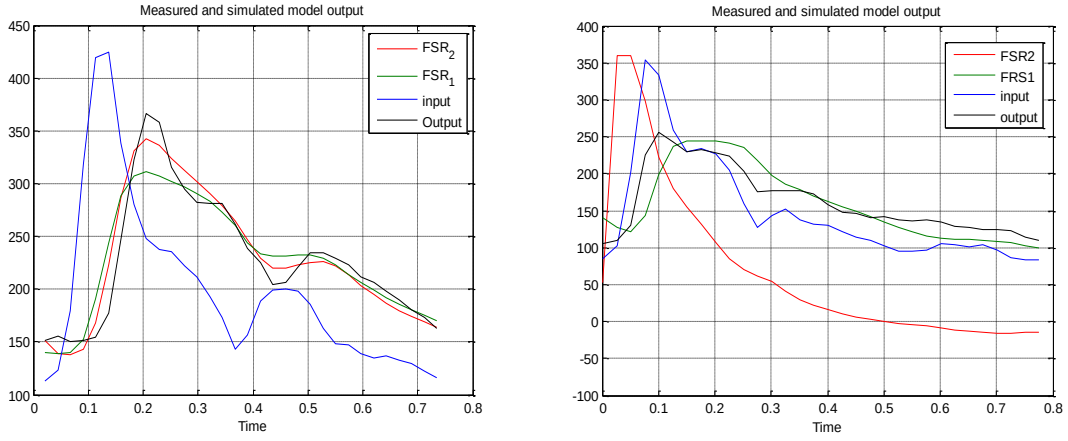

Fig. 6 Estimation of the transfer function: young subject (a) and old subject (b).

We use impulse response to derive the natural response of a system. As definition, the impulse response describes the reaction of the system as a function of time. It allows the parameterization of the dynamic behaviour of the system.

The impulse response of the carotid artery is showed in the flowing figure (fig .7):

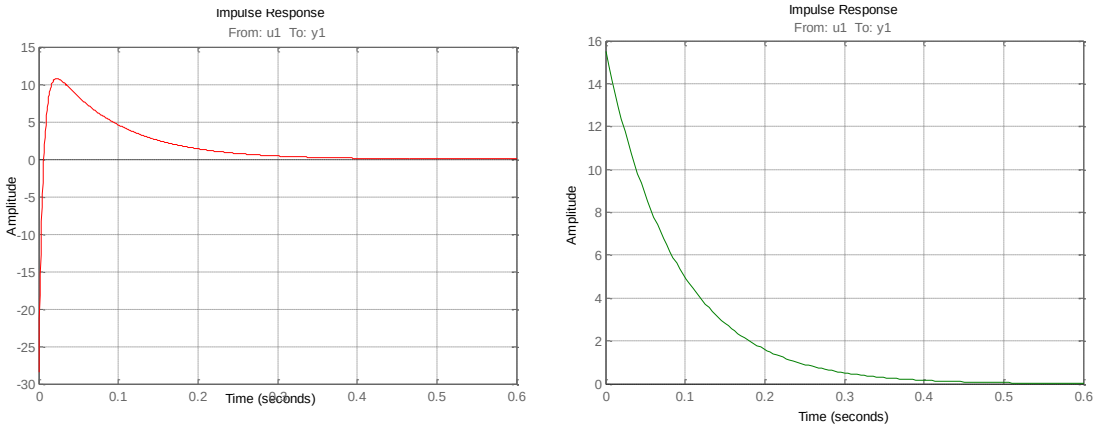

Fig. 7 impulse response: young subject (a) and old subject (b).

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Bode plot was used to illustrate the complex results, transfer functions' amplitude and phase parts are displayed separately and the amplitude part is shown in decibels (Fig. 8).

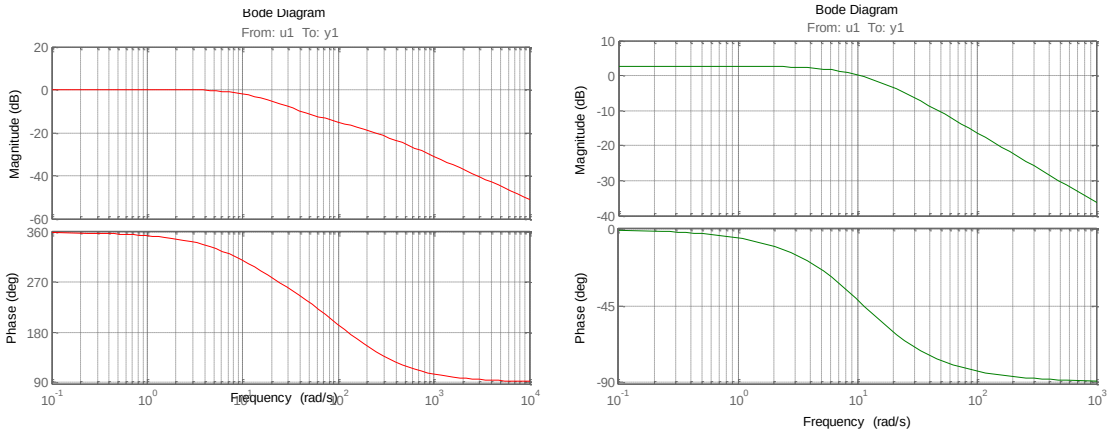

Fig. 8 bode diagram: young subject (a) and old subject (b).

TABLE II
THE RESULTS OF MEAN VELOCITIES, FUNDAMENTAL FREQUENCIES PULSATILE AND RESISTANCE INDEX FOR PATIENT DISPUTES IN THE PRIMARY AND INTERNAL CAROTID ARTERY FOR SAME SUBJECTS.

Harmonics	$V_{moy(1)}(CP)$	$V_{moy(2)}(CI)$	f_0	**PI (CP)**	**RI (CP)**	**PI (CI)**	**RI (CP)**
Young population							
Subject 1	259.59	264.81	1.18	1.49	1.27	0.92	1.42
Subject 2	226.21	227.75	1.39	1.56	1.26	0.94	1.41
Subject 3	219.59	241.5	1.16	1.54	1.26	0.89	1.42
Subject 4	294.93	224.31	1,09	1.94	1.20	1.15	1.34
Subject 5	292.93	291.56	1.38	1.42	1.27	0.89	1.41
Old population							
Subject 6	195,68	187,68	1.3	1.56	1.25	1.11	1.35
Subject 7	134.94	98.93	1.03	2.2	1.10	1.93	1.17
Subject 8	258.53	187.87	1.27	1.72	1.23	1.37	1.29
Subject 9	112.53	162.56	1.01	1.81	1.23	0.92	1.41
Subject 10	113.78	135.75	1.56	2.03	1.17	1.91	1,19

To characterised the hemodynamic of the carotid artery, we have calculate pulsatile and resistance indexes.
These parameters are presented in table (2) and table (3):

TABLE III
THE DIFFERENCE OF PI AND RI BEFORE AND AFTER BIFURCATION.

	Commune carotid	**Internal carotid**	**p-value**
PI	1.72	1.20	0.003
RI	1.22	1.34	0.004

The statistical test showed that there is a high significate difference ($p<0.005$) between the pulsatile and the resistance indexes before and after bifurcation. We showed that the PI decrease and the RI increase. Then we can conclude that the pulsatile index decrease when the resistance index increase.

In this purpose, we suggested a new noninvasively method that allows to characterize the carotid artery by calculating the transfer function. Velocity waveform measured by phase contrast MRI. Identification of arterial system mean to asses to the arteries properties and it mean also the characterization of the propagation of the velocity wave in this system.
Our algorithm allows to: (1) calculate the transfer function for the five first harmonics (2) calculate the mean value of blood velocity, pulsatile and resistance indexes and the fundamental frequency (3) estimate transfer function order.

Baledent et al used transfer function to characterize the global mechanical in the brain [18]. However, we searched here to characterize only the mechanical proprieties in the

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carotid artery that represent one form the arteries that irrigate the brain. Table 1 showed that the transfer function is lower than 1 for five first values of FFT. Then, we can conclude that there is attenuation of blood velocity between common carotid and internal. We noted that transfer function is depended from mechanical properties such as resistance. Pulsatility index was proposed by Taylor (1985) as a parameter to evaluate cerebral vascular resistance [19]. In the internal carotid artery, pulsatility index of the blood flow were employed as a parameter that evaluate a changes in cerebral vascular resistance [19].

IV. CONCLUSION

To characterize the carotid artery we have calculate: transfer function, pulsatile and resistance indexes. To obtain Transfer function, we measured the velocity of flow in two sections of the carotid before and after the bifurcation. By applying the ident toolbox of Matlab, we can estimate the order of transfer function of the system to be identified. We have found encouraged results.

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