Un-calibrated real-time Stroke Volume estimation in MRI using the MagnetoHydynamic Effect ?

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Abstract

The stroke volume (SV) is an important indicator of the cardiac function.

SV can be measured during a Magnetic Resonance Imaging (MRI). The development of a real-time SV estimation technique would benefit the MRI community.

We analysed the possibility of an un-calibrated real-time estimate of SV, by using the MRI induced distortion of the Electrocardiogram (ECG) or Magnetohydrodynamic (MHD) effect. The MHD is induced by the interaction of the blood flow, in the aortic arch, with the MRI static magnetic field. The ECG template was computed during two recordings (inside and outside the MRI), and these two templates were subtracted to estimate the MHD.

ECG data was acquired during a clinical trial, approved by the local ethics comity, and informed consents were obtained from all 9 healthy subjects (4 males, 5 females). ECG were recorded on three leads, in a 1.5T scanner (GE, USA), using a monitoring device (Schiller, France). Phase contrast Cine images were acquired, and processed to extract MRI-based SV measurements.

Gregory, et al. showed the possibility of estimating the MRI-based SV by linearly regressing the MHD from three leads. This process was used to find the four parameters of their linear model. The correlation between MRI-based SV measurements and calibrated MHD SV estimates confirmed their findings.

To assess the feasibility of an un-calibrated estimation, SV was estimated using the mean values across all subjects model parameters. The fit was poor ($R^2 = 0.3$) and with a negative correlation. The population was then divided by gender and by BMI to assess the impact of these factors. However, the fit remained still poor in both cases.

The analysis of the calibration parameters showed a huge variation across the dataset. Gender and body shape could not by themselves explain theses variations. Other factors need to be accounted for un-calibrated SV estimation.

1. Introduction

The stroke volume (SV) is the volume of blood ejected from the heart left ventricle per heartbeat. It is a good indication (along with the left ventricular ejection fraction) for Heart Failure [1].

SV is currently measured during an echocardiographic exam, but can also be performed during a Magnetic Resonance Imaging (MRI) exam [2]. It ha smorevoer been show that Cardiovascular Magnetic Resonance (CMR) shows better reproducibility than 2D echocarcardiography [3, 4]. The MRI-based measurement is an average measurement performed over several cycles, as the image acquisition is a relatively slow process lasting for at least a dozen heartbeats [5]. The development of a real-time SV estimation technique would benefit the MRI (-guided intervention) community, as it would allow for the detection of advert events during the procedure [6].

We therefore analyzed the possibility of extracting SV during an MRI exam in real-time (beat per beat) and in an un-calibrated manner, by using the MRI induced distortion of the Electrocardiogram or magnetohydronamic (MHD) effect. The MHD effect is induced by the creation of an electrical field due to the motion of electrically charged particles (in the blood) in the huge static magnetic field of the MRI. The main contribution if the MHD effect is the aortic blood flow [7], since the aorta is the largest artery, the blood flow is high, and the aortic arch is perpendicular to the MRI scanner static magnetic field. The apparition of this field yields a huge difficulty in analyzing the therefore distorted ECG signals (making any advanced analysis of the ECG signal, such as the extraction of the ST level), and can also lead to a decrease in blood velocity (Ultra high fields).

The objective of this sudy is to extend the methodology presented in [8] to estimate the SV from ECG signals acquired during an MRI examination and assess whether the suggested calibration step is required, or if an un-calibrated approach would be possible.

2. Methods

ECG data was acquired by the IADI lab, during the clinical trial (Database of ECG acquired on a 1.5T). The trial was approved by the local ethics community, and informed consents were obtained from all subjects [9]. 9 healthy subjects were included in this study (4 males, 5 females). ECG signals were recorded on three leads using a custom configuration (which remained identical throughout the clinical study), inside and outside the MR bore, (1.5T GE Signa Hdx, WI, USA). Phase contrast Cine images of the aorta were acquired, and post processed to extract the MRI-based SV measurements (along with the aera of the cross-section of the aort, the blood velocity and blood flow in the aorta) for each subject.

The data analysis was carried out on Python using the Anaconda development interface. The first step of the data analysis consisted in the extraction of the MHD effect from the ECG signals. The ECG template was computed for both acquisitions (inside and outside the MRI), by averaging teh ECG signal across thirty cardiac cycles. A subtraction of these two templates allows to get a template for the MHD effect [8]. Gregory et al. have shown that it was possible to get an estimate of the SV by calibrating the MHD effect from three leads with an MRI-based SV measurement [8]. The blood flow is linearly regressed using the three MHD signals as input values, and the SV is then deduced by integrating the blood flow over a cradiac cycle. This process was applied in order to find the four parameters of the linear regression in order to estimate SV from the MHD templates of the three leads:

$$SV_{MHD} = \int a + b \times MHD_X + c \times MHD_Y + d \times MHD_Z. \quad (1)$$

The correlation between MRI based SV measurements and calibrated MHD SV estimates was computed to confirm Gregory et al. findings. An analysis of the four parameters across the dataset was then conducted, and an estimate of SV was computed using the mean values of four parameters across the dataset, to assess whether un-calibrated SV estimation can be performed from the MHD effect.

The impact of several features, such as sex and BMI, was then studied. The dataset was divided according to each feature to assess the homogeneity of the four model parameters in each sub-population.

3. Results

Figure 1 show the process of extracting the MHD template from the ECG signals for three leads from one subject.

Figure 2 depicts the calibrated blood flow curves from the above signals. Note that only the ST portion (0.2-0.6s) was used in order to compute the SV as it corresponds to the timing of aortic blood flow.

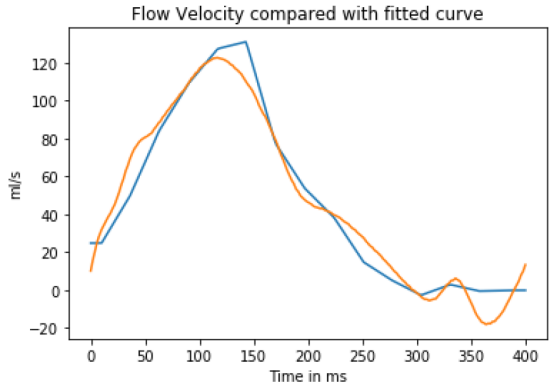

Figure 2: Comparison of Aortic Flow velocity MRI based measurement (blue) and calibrated MHD based estimate (orange).

The SV was then estimated by integrating the aortic blood flow. The calibrated MHD-based SV estimates were then compared to the MRI-based measurements. The correlation between these two estimates is clear (figure 3), with a coefficient of determination $R^2 = 0.77$.

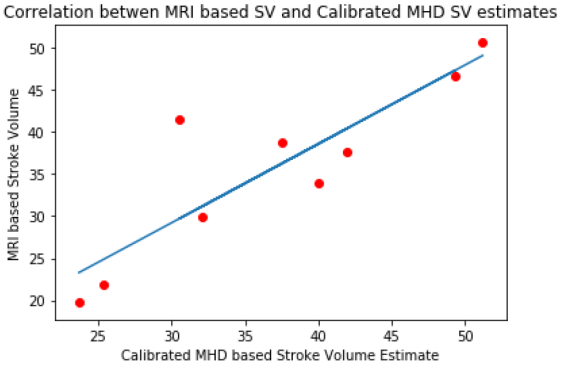

Figure 3: Comparison between MRI based SV and calibrated MHD SV estimates. In red scatterplots of SV values for each subject, and in blue the linear fit (y = 0.9x+1)

Table 1 assembles the values of the four calibration parameters (a, b, c, d) across the dataset. The mean and standard deviation values were also computed. It can be seen that the different calibration parameters have a huge variation across all subjects, which is reflected by the high standard deviation values.

In order to assess the feasibility of un-calibrated estimation of the SV using the MHD effects, SV was estimated from the mean values for all subjects, and the results are

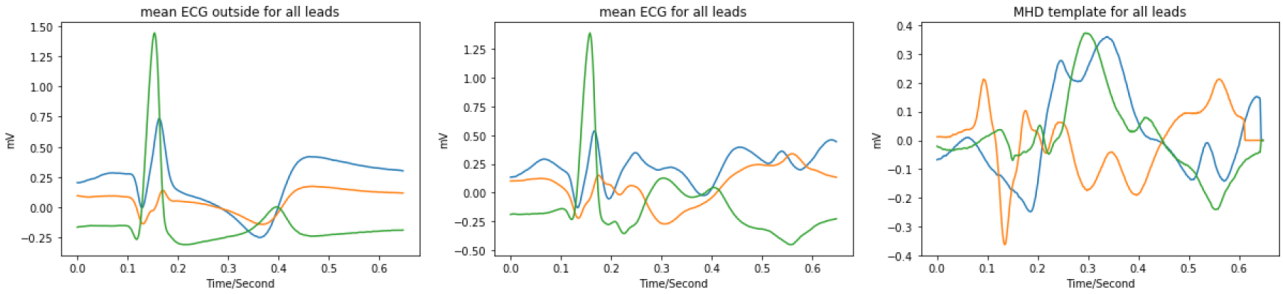

Figure 1: MHD template extraction. From left to right: ECG template outside and inside MRI, the subtraction of the two templates result in MHD template.

	# 1	# 2	# 3	# 4	# 5	# 6	# 7	# 8	# 9	**mean**	**std**
a	30.1	35.4	64.2	68.4	92.0	74.5	58.6	44.0	104.9	**63.6**	**23.5**
b	166.8	-291.9	101.4	75.8	-71.3	-152.2	129.6	30.5	-352.2	**-37.6**	**176.2**
c	-1.83	-13.2	-221.6	-483.6	-248.5	-227.8	380.7	-207.7	63.4	**-106.7**	**232.5**
d	118.4	-3.1	-22.3	-226.7	-145.5	191.3	30.5	200.2	201.8	**38.2**	**146.2**

Table 1: Values of calibration parameters across the dataset. The mean and the standard deviation (std) values are also given.

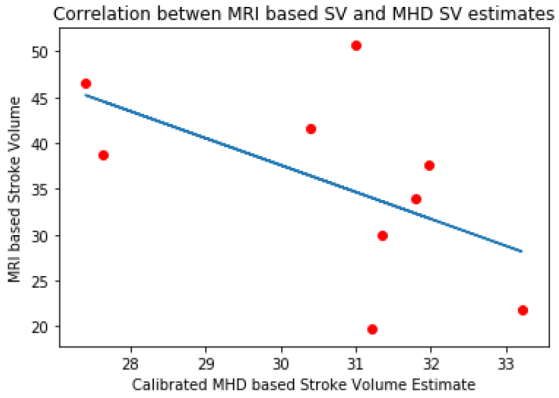

Figure 4: Comparison between MRI based SV and un-calibrated MHD SV estimates. In red scatterplots of SV values for each subject, and in blue the linear fit (y = -2.9 x + 126)

depicted on figure 4. The fit is quite poor with a coefficient of determination $R^2 = 0.30$, and a negative correlation.

The subject population was then divided by gender in order to assess whether the gender is main factor explaining the huge parameters variation. The comparison between MRI based SV and gender specific un-calibrated MHD SV estimates are depicted in figures 5. The fit was still quite poor for both genders (with coefficients of determination, male $R^2 = 0.08$ and female $R^2 = 0.04$).

The subject population was then divided by BMI in order to assess whether the subject body shape is main factor explaining the huge parameter variation. All subjects were in the normal weight category, the threshold for dividing the population was set to 22. The comparisons between MRI based SV and BMI specific un-calibrated MHD SV estimates are depicted in figures 6. The fit was still quite poor for both BMI categories (with coefficients of determination, $BMI > 22$ $R^2 = 0.07$ and $BMI < 22$ $R^2 = 0.60$), and negative correlations.

4. Discussion

This study confirmed that MHD effects could be used for estimating the Stroke Volume after a calibration as shown in the literature [8].

The analysis of the calibration parameters also shows that there is a huge variation even across a relatively small database, and that a standard set of parameters cannot be used in order to estimate the SV in an un-calibrated manner.

Gender and body shape were the two factors tested in order to understand the main mechanism explaining these huge variations. Neither factors were able to get accurate un-calibrated SV estimates. It would be interesting to perform further analysis of the factors behind the parameter variations, geometry of the aorta and the variability of electrode positions are probably key factors to test in priority. It would be interesting to assess whether a standard 12-lead configuration would allow for an uncalibrated SV estimate.

There is still the need to develop an accurate real-time MHD extraction technique, a Bayesian filter has been recently suggested [7].

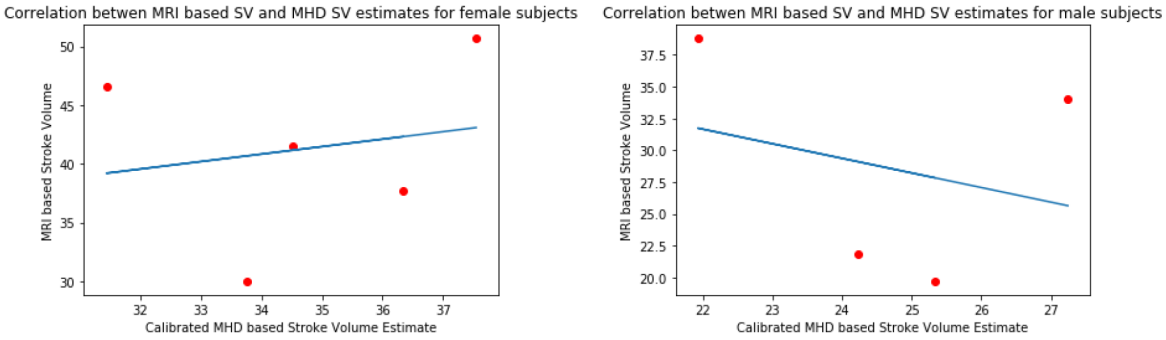

Figure 5: Comparison between MRI based SV and gender specific un-calibrated MHD SV estimates (left: female subjects right: male). In red scatterplots of SV values for each subject, and in blue the linear fit (male: y = -1.1 x + 56.9, female : y = 0.6 x + 19.2).

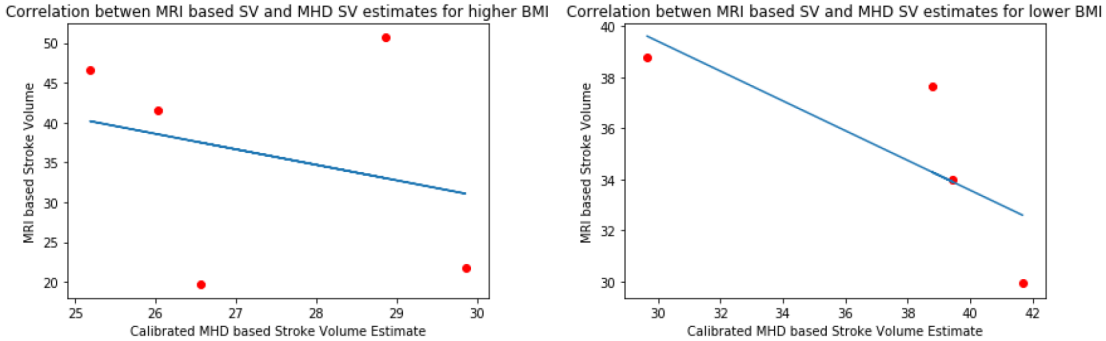

Figure 6: Comparison between MRI based SV and gender specific un-calibrated MHD SV estimates (left: higher BMI right: lower BMI). In red scatterplots of SV values for each subject, and in blue the linear fit ($BMI > 22$: y = -1.9 x + 89.3, $BMI < 22$: y = -0.6 x + 56.9).

In conclusion, it is not yet possible to derive a SV estimation from the MHD effect in an un-calibrated way. The main factors behind the calibration parameter variation have still to be determined.

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