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Ergonomics and workflow evaluation of automatic doppler angle technology implemented in a diagnostic ultrasound system

F. Vannetti[a], T. Atzori[a], S. Matteoli[b], F. Andreuccetti[c], M. Fabiano[d], P. Menini[d], S. D'Onofrio[d], L. Forzoni[c]

[a]*Fondazione Don Gnocchi, Florence, Italy*
[b]*Department of Industrial Engineering, Università degli Studi di Firenze, 50139 Florence, Italy*
[c]*Esaote S.p.A., Florence, Italy*
[d]*Esaote S.p.A., Genova, Italy*

Abstract

Commonly available Pulsed Wave Doppler (PW) flow velocity measurements for Ultrasound (US) investigation require the operator to manually set the direction of the flow velocity vector along the blood vessel axis on the US image, in order to determine the Doppler angle and then to estimate the real flow velocity. The present work investigates the possibility to implement on a commercially available US system an innovative Automatic Doppler Angle (ADA) Technology by analyzing the best workflow in terms of higher execution speed, lower keystrokes/adjustments helping in the prevention of Work-related Musculoskeletal Disorders (WRMSD) and a Doppler angle correction precision, comparable to the one obtained manually by expert sonographer. Ergonomics and workflow tests, then accuracy and repeatability evaluations of the Doppler velocity measurement, were performed on a portable US system (MyLabAlpha, Esaote S.p.A., Florence, Italy) by an expert sonographer. Ergonomics and workflow Tests were performed to analyze the potential of ADA in terms of reduction of muscular activation applied (by SEMG), number of activations (by cameras optoelectronic system) and time needed using ADA, in comparison to manual procedure. Accuracy and intra-operator repeatability tests of the velocity measurement were performed to evaluate the precision of the obtained PW trace velocity measurements with ADA technology, compared to manual ones. Results provided evidence that ADA tool allowed: a reduction of muscular activation (from 12% for trapezius descendens, to 25% for deltoideus anterior) a lower total number of keystrokes and a reduction of the US scan time of about 56%. The maximal variation between PW Doppler trace velocity measurement set automatically by ADA and set manually by sonographer was 11%. ADA technology can provide a Doppler angle correction precision comparable to the manual one, while decreasing the risk of WRMSD.

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Keywords: Blood velocity; Work-related musculoskeletal disorders; Surface electromyography; Common carotid artery

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Nomenclature

WRMSD	Work-Related Musculoskeletal Disorders
ADA	Automatic Doppler Angle
ADM	Automatic Doppler Measurement
US	Ultrasound
PW	Pulsed Doppler
CFM	Color Doppler
SV	Sample Volume
CCA	Common Carotid Artery
ROI	Region of Interest
SEMG	Surface Electromyography

1. Introduction

Color Doppler Ultrasound systems are nowadays widely available and, from a clinical perspective, vascular evaluations are widely common regarding prevention, diagnosis and follow up of many pathologies. Therefore, the execution of blood flow velocity measurements is really common and repetitively performed in many clinical examinations (just to name a few: Peripheral Vascular, Venous Lower Limbs, Adult and Pediatric Cardiology, Neurosonology, Ob-Gyn, etc…). This is the reason why a tool which would enable the increment of efficiency and at the same time would reduce the number of keystrokes, decreasing time needed and fatigue,is of main interest in such a context.

The term Doppler indicates the technique used to measure the blood flow, based on the natural phenomenon studied by the Austrian physicist Christian Johann Doppler (1803-1853).

The Doppler Effect (or Doppler shift) is an apparent change in wave frequency perceived by a fixed observer respecting to the moving source of the waves. It is commonly heard when a vehicle, sounding a siren or horn, approaches, passes, and recedes from an observer: the received frequency is higher (compared to the emitted frequency) during the approach, it is identical at the instant of passing by and it is lower during the recession. Pitch modifications are related to the speed of the vehicle and its direction.

In US imaging the wave isn't transmitted by a moving object (vehicle), but by a fixed object (probe). In US examination echoes received from fixed tissues will be at the same frequency as the transmitted beam. If echoes received are from moving structures, as blood cells, the transmitted and received frequencies will not be the same ones and the generated echo will vary in direct ratio to the velocity and direction of the movement itself.

The shifted frequency is used to determine the relative velocity and direction of this moving structures (blood flows). The greater the frequency shift, the higher the velocity of the moving object. Movement toward the transducer results in a higher received frequency; whereas movement away from the transducer results in a lower received frequency. The Doppler Effect can be expressed by the following formula:

$$fd = \frac{2 f_t V \cos\theta}{c} \tag{1}$$

where f_d indicated the Doppler shift, c the speed of sound in tissue, f_t the transmitted beam, V the blood velocity, and θ the angle of incidence between the ultrasound beam and the direction of the flow [1].

It has to be noted that US beams must always have a position not perpendicular to the flow under investigation otherwise there will be no Doppler Effect. The linear probes allow US electronic beam steering in the longitudinal scan.

In Pulsed Doppler (PW) a single transducer is used for both transmission and reception, providing Doppler shift data selectively from a small segment of the ultrasound beam called Sample Volume (SV)**.** It performs analysis of all the frequency variations, so it gives a real-time representation of all the velocities versus time (Fast Fourier

Transform - FFT - for spectral analysis): it is thus possible to discriminate, even mathematically, peak velocities from the average and minimum ones [1].

PW is enabled by positioning the SV on the vessel to be examined: a pulse is sent out from the transducer and the frequency shift in the reflected pulse is measured after a certain time. By using the Doppler equation (1), the echo information obtained within the SV is analyzed for shifted frequency and amplitude, so that the blood velocity can be determined. This process is alternately repeated through many transmitted-received cycles each second, in order to obtain enough data to calculate the frequency components of the sampled volume. The frequency data are converted to velocity and displayed in a scrolling strip format on the monitor (spectrum).

Color Doppler (CD) provides a bi-dimensional representation of blood flow in real time. CD detects the velocity and direction of a flow using similar principles of PW Doppler, but the detection does not take place within a single sample volume, but in several sample volumes at once. Their number depends on the number of lines, where the measurements take place, and the number of sample volumes along each line. The CD examined area depends on the size of the window sampling, which is operator adjustable [1].

A color is assigned to the calculated velocity data, to represent a certain velocity and direction, and then they are displayed in a Color Box over-imposed on the B-Mode image. CFM is enabled by positioning a window sampling on the image area to be investigated. The Color Box allows all flows included to be viewed, specifying their direction, speed and eventual turbulences (Fig. 1).

Existing Doppler flow velocity measurements for US investigation require the operator to 1) manually set the direction of the flow velocity vector along the blood vessel axis on the US image, 2) determine the Doppler angle and then 3) estimate the real flow velocity [2-4].

A different dual-beam approach, recently developed [2-4], uses one beam (reference) to identify the flow direction, and the second one (measuring) to directly estimate the true flow velocity at known beam-flow angle. The operator only takes care of locating the Doppler sample volume in the region of interest (usually the centre of the vessel) and, through the extraction of appropriate parameters from the Doppler spectrum, the reference beam is automatically steered toward the right orientation to the flow. The velocity magnitude is, thus estimated by the measuring beam, which is automatically oriented with respect to the (known) flow direction at a suitable Doppler angle.

The Automatic Doppler Angle (ADA) technology based on the Dual Beam approach has been recently implemented in a prototype of a commercially available US system. The Dual Beam tool, developed by the MSDLab, University of Firenze, Italy, was initially implemented on a US research based open platform (Ula-Op, MSDLab, University of Firenze, Italy - [2-4]) with the aim of improving the precision of the Doppler correction angle selection, depending on the examined vessel regarding morphological characteristics and transducer position with respect to the vessel itself.

The implementation of this tool on a commercially available platform would have the main aim to deliver to the final user a Doppler angle correction precision comparable to the one obtained manually selecting the best angle (that is within the same error range) while speeding up the Doppler correction angle selection phase and reducing the number of keystrokes/adjustments which are needed to obtain the desired Doppler correction angle, by the activation of a single button. This would provide enhanced ergonomics, with lower risk of Work-Related Musculoskeletal Disorders (WRMSD), as Doppler US vascular examinations are very common within many clinical applications.

The present work investigates the implementation of the ADA Technology on prototype scanner based on a commercially available US system (MyLabGamma, Esaote S.p.A., Florence, Italy), analyzing its workflow in terms of higher execution speed and lower keystrokes/adjustments in comparison with the standard manual Doppler angle correction, and its precision in comparison to the one obtained manually by an expert sonographer.

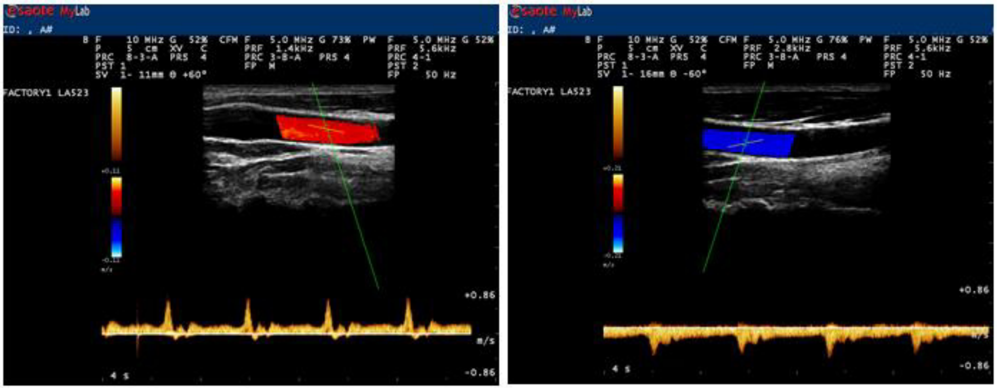

Fig. 1. Example of Common Carotid Artery examination with CD and PW - Left image upper part: CD signals of the blood flow moving toward the transducer are shown in red; Right image upper part: CD signals moving away from the probe are shown in blue; Left image lower part: PW signals moving oward the transducer are shown with a positive spectrum; Right image lower part: PW signals moving away from the probe are shown with a negative spectrum.

2. Material and methods

Ergonomics and workflow tests [5, 6], as well as accuracy and repeatability evaluations of the Doppler velocity measurement [7-9], were performed on a portable US system with embedded ADA technology, by an expert sonographer on two healthy subjects who underwent a vascular examination of the Common Carotid Artery (CCA) performed by applying a standard scanning manual protocol as well as the same examination using the ADA tool. The sonographer used the US system with the left hand, handling the probe with the right one during the scanning protocol. US examinations were performed with the operator facing the examined subject, who was laying on the operator's right side (Fig. 2(a)). Manual examination was performed according to the following scanning protocol:

- B-Mode Imaging activation
- Activation of the CD and positioning of its Region of Interest (ROI) over CCA
- Activation of the Doppler line of sight
- Positioning of the PW Doppler SV
- Steering of the Doppler line of sight
- Doppler correction angle main adjustment (in terms of 0°, 30°, 60°)
- Fine tuning Doppler correction angle (in terms of corrections of 2° per step)
- Activation of the PW Doppler
- Recording of two heart cycles of PW Doppler trace
- Freeze

Examination performed using the ADA technology, was performed according to the following scanning protocol**:**

- B-Mode Imaging activation
- Activation of the CD and positioning of its ROI over CCA
- Positioning of the PW Doppler SV
- ADA activation
- Activation of the PW Doppler
- Recording of two heart cycles of PW Doppler trace
- Freeze

Note that performing ADA technology, the operator has only to activate the Doppler line of sight and then to position the PW SV over the vessel where the blood flow measurement has to be performed.

Ergonomics and workflow tests were performed to analyse the potential of ADA technology in comparison with the manual procedure, in terms of: 1) muscular activation through a Multi-channel Wireless Superficial Electromyography (SEMG) (Freemg300, BTS S.p.A., Milano, Italy); 2) number of kinematic activations through a camera optoelectronic system (SmartDx400, BTS S.p.A., Milano, Italy) and 3) US execution time, necessary to select the correct Doppler line of sight steering and Doppler correction angle selection during a total of ten US scans, through a chronometer.

A total of six SEMG sensors were placed on sonographer's left arm (Figure 2 (b)). Calibration procedures were carried out before starting each experimental session. SEMG data were processed with Matlab by using a high-pass filtering at 20Hz.

Accuracy and intra-operator repeatability tests of the velocity measurement were performed to evaluate the precision of the obtained PW Doppler trace velocity measurements with ADA technology, compared to the Doppler angle manual adjustment ones. PW trace velocity measurements were performed in two ways: averaged Vpeak (velocity peak) automatically measured by using Automatic Doppler Measurement (ADM) Algorithm; Vpeak instantaneous maximum velocity, performed manually by the skilled operator.

ADM is a technology [10] developed in order to measure more periods of a PW Doppler trace and then to obtain averaged velocity measurements related to mean and peak velocities. When ADM is active, a proper contouring of the peaks of the Doppler trace is performed. The ADM algorithm works in such a way to detect and perform automatically the velocity measurements over the Doppler trace, which would be performed manually, in more time, by the operator. Figure 3 shows ADM (represented by the trace border highlighted by the arrow) on 2 heart cycles.

A total of 14 procedures of Vpeak measurements were performed, considering both the Vpeak and the averaged Vpeak over two heart cycles (calculated with ADM).

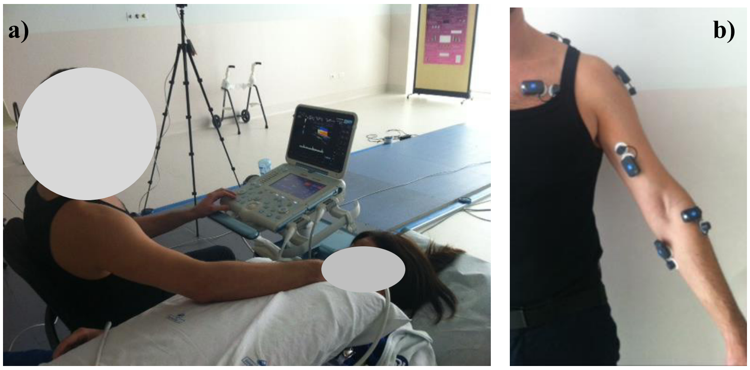

Fig. 2. (a) Sonographer's posture during US scanning; (b) SEMG sensors placed on the sonographer's left arm.

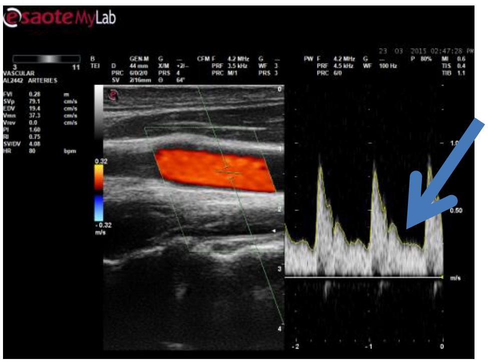

Fig. 3. ADM on three cycles. The ADM is graphically represented by the yellow trace border highlighted by the arrow.

3. Results

3.1. US execution time analysis

The manual procedure needed an average of 8 keystrokes/adjustments more than those used during ADA. This difference implied a reduction of the US execution time when using ADA (9.73 ± 1.20 s) in comparison with the manual use of the system (22.4 ± 3.19 s) of about 56%.

3.2. SEMG analysis

SEMG analysis provided evidence that ADA tool allowed a reduction of the mean muscular activation during the entire US examination, especially for the deltoideus anterior (25%), pectoralis major (19%) and trapezius descendens (12%), as shown in Fig. 4. Fig. 5 shows the SEMG amplitude, normalized to rest SEMG, of the left trapezius descendens, recorded during both manual and with the use of ADA tool procedure. Only the left flexor carpi radialis showed a higher activation (27%) during ADA tool (Fig.4). At this regard, the sonographer's scanning posture must be taken into consideration. Specifically, Fig. 6 shows the normalized SEMG of left flexor carpi radialis during ADA tool: the black line indicates the time corrisponding to the muscle contraction due to the position of the sonographer's wrist rested on the cart frontal handle with flexed fingers.

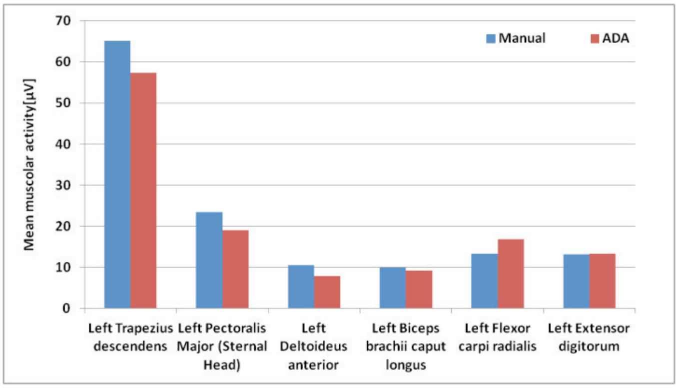

Fig. 4. Main muscular activation measured during both manual procedure (blue) and ADA tool (red).

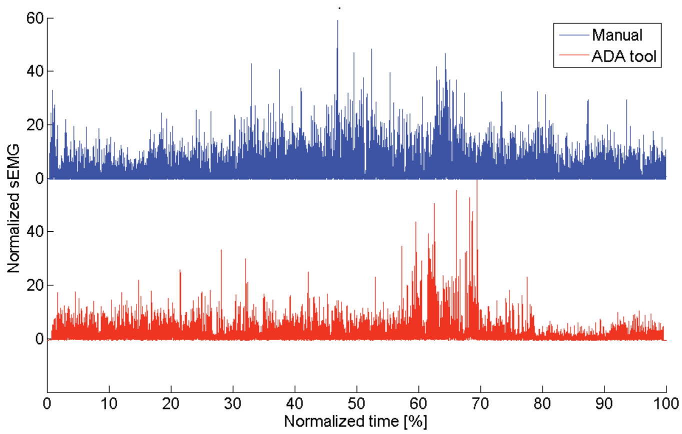

Fig. 5. SEMG of left trapezius descendens during manual procedure (blue) and ADA tool (red).

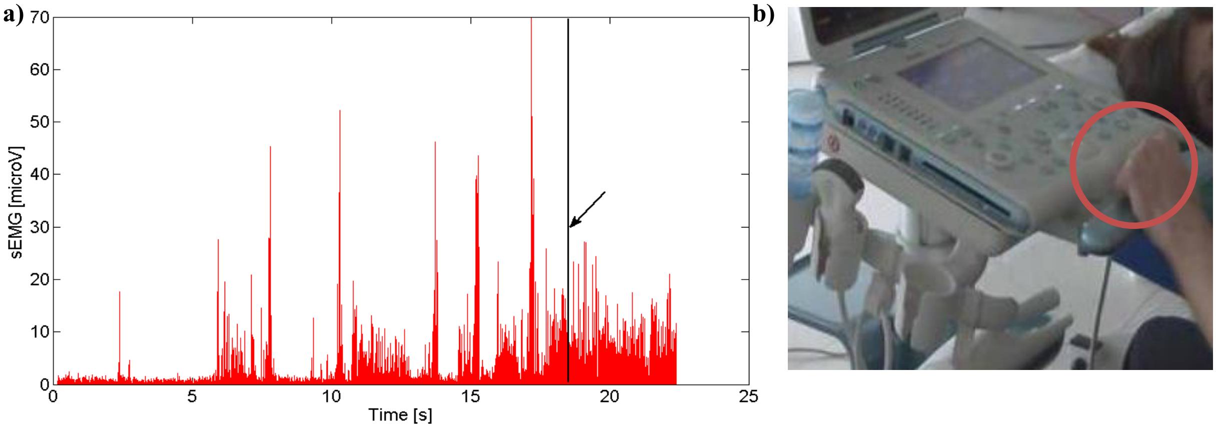

Fig. 6. (a) SEMG of left flexor carpi radialis during ADA tool: the black line indicates the time corresponding to the muscle contraction due to the position of wrist rested on the keyboard bar with flexed fingers (b - red circle).

3.3. Precision and intra-operator repeatability tests

Precision and intra-operator repeatability tests of the velocity measurement were performed to evaluate the precision of the obtained Pulsed Wave (PW) Doppler trace velocity measurements with ADA technology, compared to standard manual procedures performed by the skilled operator. Specifically, PW Doppler trace measurements were carried on taking into consideration Automatic Doppler Measurement (ADM) and manual measurement of the instantaneous velocity. In both cases the maximum velocity (Vpeak) was considered. It has to be noted that the ADM was averaged on 2 heart cycles. The maximal variation between PW Doppler trace velocity measurements automatically set by ADA technology and manually set by sonographer was 11% , as shown in Table 1.

Table 1. PW Doppler trace velocity measurements automatically set by ADA technology and manually set by the sonographer.

Test # ADM (Vpeak) – averaged on 3 cycles	Manual setting of steering ad Doppler angle (cm/s)	ADA (cm/s)	Delta ADA with respect to manual	
1	97.9	96.8	-1.1	-1.1%
2	53.8	48.0	-5.8	-10.8%
3	-88.1	-97.7	9.6	10.8%
4	-98.4	-94.1	-4.3	-4.3%
5	-93.3	-93.3	0.0	0.0%
6	46.6	51.8	5.2	11.1%
7	78.1	82.9	4.8	6.1%
Test # Manual Measure (Vpeak)	Manual setting of steering ad Doppler angle (cm/s)	ADA (cm/s)	Delta ADA with respect to manual	
1	102.0	97.6	- 4.4	-4.3%
2	-90.3	-100.4	10.1	11.1%
3	-99.5	-97.4	-2.1	-2.1%
4	-93.9	-88.8	-5.1	-5.4%
5	-97.6	-101.3	3.7	3.8%
6	51.6	53.4	1.8	3.5%
7	85.5	86.6	1.1	1.3%

4. Discussion and conclusion

ADA represents a new concept of workflow for Doppler measurements, enabling the steering of the Doppler line of sight and the set of the Doppler correction angle in a single touch. Our findings showed that the use of ADA reduces the number of keystrokes/adjustments and thus reduces US execution time of approximately 56%. Furthermore, SEMG data showed a lower contraction (about 18%) of all muscles that may be involved in the shoulder pain and stress-related pathologies reported by the sonographers [5]. Only the flexor carpi radialis showed a higher activation during the use of ADA. This may be explained by considering that an automated procedure such as ADA would allow a longer resting position of the sonographer's left wrist with flexed fingers on the US keyboard bar. The increase of muscular activity is thus completely due to the sonographer's static posture, which does not depend on the protocol/procedure applied and can be reduced by changing the scanning posture during the US examination.

Accuracy and intra-operator repeatability tests of the velocity measurement were performed to evaluate the precision of the obtained Pulsed Wave (PW) Doppler trace velocity measurements with ADA technology, compared to standard existing procedures performed by the skilled sonographer. Manual and ADA tests were performed, necessarily, in two different time frames. Specifically, during the tests the first measurement was acquired by performing manually both steering and Doppler correction angle adjustment and, after this, the same measurement was performed using ADA for the steering and Doppler correction angle selection. This necessarily obliges the user to perform the velocity measurements on two physically different PW traces, acquired in different time frames, with possible movements of the probe/patient neck due to swallowing, probe minor movements along the examined vessel (longitudinal direction) and also in the transverse direction (selecting the diameter in one case and a cord of the vessel section in another case, for instance). Another possible reason of differences in terms of measurements can be due to real velocity changes of the examined vessel between the time frame of the manual test and the one of the ADA test. This can be originated by heart rate changes. However, the maximal variation between PW Doppler trace velocity measurements automatically set by ADA technology and manually set by sonographer was 11%, which represents a practically acceptable range of variability. Therefore, ADA technology can provide a Doppler angle correction precision comparable to the manual one, while decreasing the risk of WRMSD and reducing examination time.

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