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Multigate Quality Doppler Profiles Technology in Vascular, Obstetrics and Cardiology Applications

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Abstract

Multigate Quality Doppler Profiles (QDP) is a Fast Fourier Transform (FFT) - based Doppler technology recently integrated within a commercial ultrasound scanner. QDP represents a novel analysis tool, which is able to simultaneously detect and show the velocity components, present in the blood flow of multiple vessels, without any frame rate reduction. QDP can be used in conjunction with the DIR algorithm to enhance the visibility of the flow direction information. The present work describes the use of QDP in Cardiology (Pediatric and Adult), Vascular (cervical venous and arterial system) and Obstetrics (uterine arteries). In vivo and in vitro tests are reported, showing the QDP behavior with respect to insonation angle changes and its advantages with respect to classic Doppler technologies. The QDP is demonstrated to be a precise positioning tool for the Pulsed Wave Doppler (PW) sample volume (SV) and a qualitative direct real time indicator of blood flow variations. It is also shown ideal for the study of turbulent flow, for minor reflux detection and for easier sampling of the blood flow signal within the examined vessel (or vessels) in case of movements.

1 Introduction

QDP is a technique processing the echo signals backscattered from multiple depths along the ultrasound beam to produce and display the spectral profiles in real-time. These profiles provide direct qualitative as well as indirect quantitative information about the blood flow velocity distribution in one or multiple vessels at the same time. In the present work, this technology was tested in vitro as well as in different clinical applications and in different vessels, with a variety of transducer typologies. The considered clinical studies were:

- Vascular, regarding both arteries and veins at the neck district level (Common Carotid Artery – CCA, Internal Jugular Vein – IJV and Vertebral Vein VV) [1]
- Cardiology, regarding both Adult and Pediatric (Aorta and Inferior Vena Cava - IVC) [2-3]
- Obstetrics, about the study of uterine arteries in pregnancy [4-5]

In all cases, QDP was used together with classic Doppler technologies such as PW and Color Doppler (CD), as well as a stand-alone Doppler tool. Longitudinal scanning of the examined vessels was considered with linear and convex transducers.

2 Methods

The QDP technology, developed by the Microelectronics Systems Design Laboratory of the University of Firenze (Italy), was integrated in a commercial diagnostic ultrasound scanner (MyLab30Gold, Esaote S.p.A., Italy). The QDP tool was made available with all US probes compatible with the PW modality. In particular, the probes used for the present work where: a phased array probe with frequency range 1–4 MHz (PA240, Esaote, Imaging frequencies: 2.0–2.5–3.5 MHz; Doppler frequencies: 2.0–2.5 MHz); a linear array probe with frequency range 3–11 MHz (LA332, Esaote, Imaging frequencies: 3.5–5.0–6.6–10.0 MHz; Doppler frequencies: 3.3–5.0 MHz) and a convex array probe with frequency range 1–8 MHz (CA631, Esaote, Imaging frequencies: 2.5-3.5-5.0-6.6 MHz; Doppler frequencies: 2.5–3.3 MHz).

QDP is a Multigate Spectral Doppler technology that processes the echo signals backscattered from multiple depths along the US beam, producing and displaying in real-time the so-called spectral profile [6]. This is a matrix of power spectral densities corresponding to the simultaneously investigated depths.

The spectral profile is obtained by calculating, through the classic Fast Fourier Transform (FFT) algorithm, the Doppler spectrum of the echo samples gathered from one depth and by repeating the procedure over 128 or 256 consecutive depths (covering a total length up to 9 cm).

The QDP approach extends the known benefits of spectral analysis [7] to a large depth range without sacrificing the axial resolution. QDP technology investigates the "third dimension of Doppler" in graphical form, where spatial distribution is on the vertical axis and velocity on the horizontal one, while the brightness of any pixel describes the power of the corresponding spectral density. In this way, QDP enables the simultaneous analysis of different vessels (and different blood flow components within the same vessel) in real-time, without any frame rate reduction.

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The spectral profiles are presented in frames displayed in color coded images where the stronger frequency components are represented with lighter color.
The QDP Velocity Profile was associated to the B-Mode plus CD reference image or to the PW sonogram related to a selected SV (see Image 1).

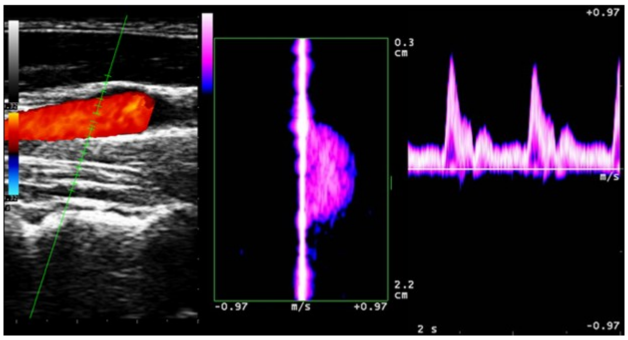
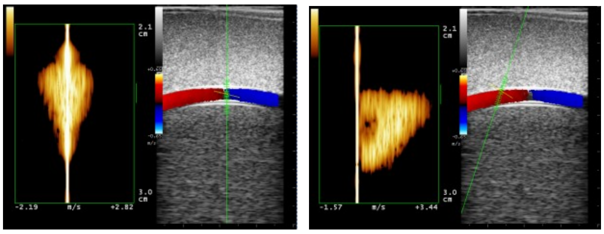


Image 1 CCA CD representation of a CCA (left): the QDP method is applied to the echoes backscattered along the highlighted Multigate line to produce the spectral profile (center). The sonogram (right) corresponds to the profile region with highest velocities.

The data contained in the QDP spectral profile can be further processed to highlight the flow direction. The mean frequency in correspondence of each gate is calculated and assumed as reliable indicator of flow direction. As such, the mean frequency profile is amplified and suitably superimposed to the spectral profile in the shape of a continuous line which gives immediate evidence to either positive or negative flow. Because of its ability to clearly show the flow direction, the algorithm, which examines the Multigate Doppler signal in real-time and extracts the mean frequency profile, was named DIR algorithm, while the displayed curve is indicated as "DIR Line" [8].
The QDP approach was first tested in vitro through a Doppler phantom including a curved tube (Model 453 - Dansk Fantom Service – Frederikssund, Denmark) to evaluate the effect of the insonation angle on the QDP spectrum. The in vivo study included 124 volunteers (41 men and 83 women) with mean age of 29 years (range 2-64). The examined subjects were patients scheduled for standard US Doppler examination. The use of the QDP tool yielded an average additional time of 4 minutes per exam. US examinations were performed by 4 expert sonographers.

3 Results

The curved tube present in the used phantom created an asymmetrical distribution of velocities, with higher velocities close to the upper wall [9].
When the Multigate QDP line of sight was perpendicular to the flow, the QDP signal gave evidence to the expected "mirror effect" [10]. Enhancing the angle of incidence, the spectral power was moved toward the positive frequencies (see Image 2). However, the in vitro experiments clearly showed that the contour of the spectral profile maintained the same shape while the insonation angle was changed.



(A) (B)

Image 2 In vitro test for insonation angle dependency. **A:** Multigate QDP perpendicular insonation with respect to the target flow; **B:** Decreasing the insonation angle (45°), QDP enhances the signal amplitude without changing the spectrum shape.

In vivo examinations performed on the cervical venous system were first focused on the detection of refluxes within the VV and IJV.
By displaying the mean frequency profile (DIR Line) in real-time and after suitable amplification and processing (DIR Algorithm) of the QDP signal, a direct indication of blood flow direction of both the weak/slow and the strong/high velocity signals, detected in the examined vessels, was obtained, thus overcoming the limitations of PW and CD [11] (see Image 3).

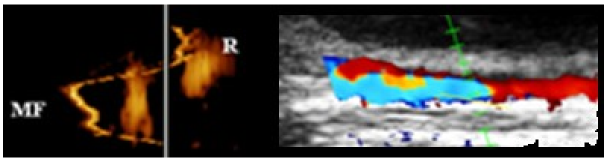


Image 3 IJV minor reflux clearly detectable with QDP DIR but not clearly detected with CD.

QDP also enabled a detailed qualitative evaluation of blood flow changes within the examined vessels (see Image 4). With respect to standard PW Doppler the addition of spatial information represented a practical help to follow the signal in real time without the limitations of US triplex (B-Mode, CD and PW active at the same time) also in case of movements of the examined vessel or of surrounding structures (due to neck movements or increased respiratory activity).

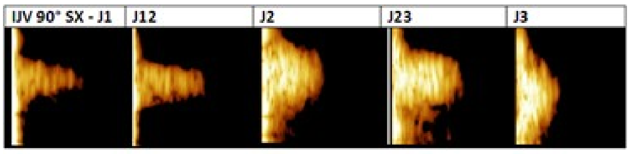


Image 4 QDP evaluation of the IJV blood flow in different segments with the examined subject at 90° (seated).

QDP technology was also used for CCA blood flow study. Particular attention was taken in case of a CCA stenosis. QDP was used to evaluate the blood flow before, above

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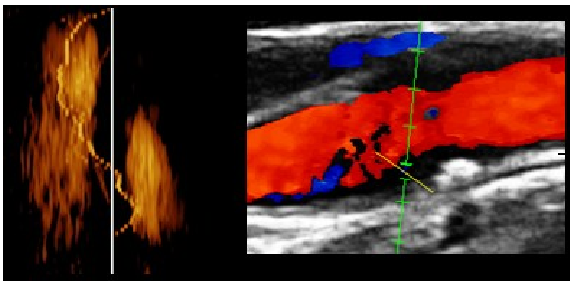
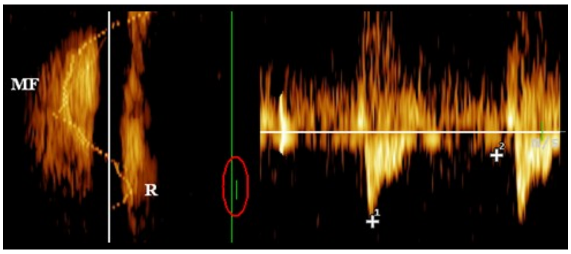
and after the plaque. The QDP gave evidence to the turbulent flow present in these regions, with higher spatial and temporal resolution with respect to CD. QDP enabled the visualization of the velocity components present within the turbulent flow after the stenosis, without the overwriting effects obtained with CD [11]. Sometimes, QDP showed the reflux signal even if CD failed. Moreover, in this site, the QDP helped for the precise PW SV positioning (SVP). See Image 5.



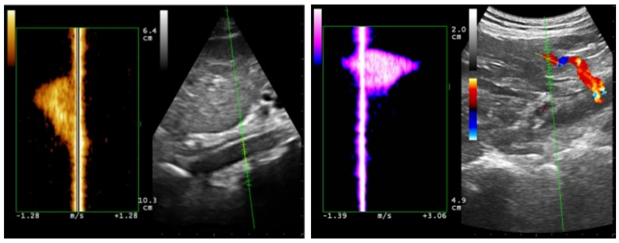
(A)



(B)

Image 5 A: QDP DIR used for the detection of blood flow reflux after stenosis in CCA while CD failed. **B:** QDP DIR used for the precise PW SVP over the reflux in order to measure the maximum velocities.

In Adult Cardiology, QDP was used for the evaluation of the retrograde diastolic flow in aortic arch as an indirect method for the evaluation of the severity of aortic insufficiency [3]. The QDP was of help regarding the PW SVP for the reflux evaluation and analysis of the turbulent flow.
In Pediatric Cardiology, QDP was used for the analysis of blood flow in the IVC with particular attention to the study of subjects who underwent the Fontan surgical intervention in case of univentricular hearth defects [12]. In this case different blood flow profiles than the laminar one were shown, overcoming the CD overwriting and helping in the PW SVP for the measurement of the maximum velocity.
In Obstetrics application, QDP technology was used for the evaluation of blood flow within the uterine arteries considering patients for pre-eclampsia screening [4-5] (see Image 6). QDP enabled a practically feasible way for precise PW SVP, overcoming the limitations of triplex in case of deep respiratory activity. In this case, the abdomen of the pregnant patient was subject to large movements, which negatively affected the PW SVP. Thanks to the multigate coverage up to 9 cm, QDP was able to follow the vessel movements without the frame rate, maximum velocity and acquisition quality limitations of triplex (B-Mode plus CD plus PW).



(A) (B)

Image 6 A: QDP signal of Inferior Vena Cava in univentricular pediatric subject; **B:** QDP signal in uterine artery in a pre-eclampsia pregnant subject.

4 Conclusion

QDP technology allowed to extend the high sensitivity of spectral analysis to multiple gates. When one or more vessels were intercepted by the same Multigate line, all the blood flow directions and different flow components present within the examined vessels were simultaneously analyzed in real-time.
Displaying the mean frequency profile, after suitable real-time amplification and processing (DIR Algorithm), QDP was shown useful to give immediate evidence of the flow direction of both slow and weak flows and stronger, higher velocity signals.
Considering the performed test in different clinical studies, QDP was demonstrated a valuable tool for the following aspects:
1 - Accurate placement of the PW SV especially in case of blood flow velocities which were distributed asymmetrically within the vessel lumen. In particular in pediatric cardiology and obstetrics application, an asymmetrical velocity distribution was really common. Performing the measurement in the center of the vessel (basing the positioning on the CD only) led to incorrect sampling and velocity measurements in PW mode. The same problem of PW SVP was present also in stenotic CCA analysis [13]. Also in this case the QDP tool helped in PW SVP over the portion of blood flow with maximum velocities.
2 - Study of turbulent flows. Those types of flow were present in CCA after medium and severe stenosis and in the IJV at the level of the inferior bulb. In those conditions, the CD was not able, in many cases, to properly follow the flow variations in time and space, due to overwriting and persistence problems [14]. QDP, especially with a proper color map choice, enabled to follow the velocity profile and, in particular, the spectral density distribution. This was useful for a better comprehension of hemodynamics in the vessel areas which were not evaluable up to now.
When the only interesting information was the direction, the DIR algorithm was used. In this case the DIR Line was able to follow the blood flow direction variations up to the limit of the persistence introduced for easier direction depiction for the operator's eye. In the cases were the Dir line was not able to follow too fast variations of blood flow, the QDP alone was used in order to avoid direction indication errors. The same limit was present regarding Aliasing: it was detected by the QDP but not followed by

the DIR line. Therefore, when the QDP was in Aliasing, the DIR algorithm was switched off and the direction info, even if less immediate, was detected using the entire spectral profile information.

3 - As a qualitative direct (and quantitative indirect), real time indicator of blood flow variations. Especially in the study of the IJV, where some veins drain and some other bring blood, the QDP showed to be a reliable tool for the evaluation of the blood flow variations in different sections of the same vessel. Moreover, QDP enabled the study of blood flow changes within the same vessel during inspiration activity and particular respiratory maneuvers (Valsalva, Muller's and deep inspiration were tested). The evaluation in different segments of the same vessel was performed moving the Multigate QDP line of sight along the IJV (the probe had to be repositioned if the investigation area was larger than the probe width). The evaluation of the same section in different conditions was performed with the Multigate QDP line of sight kept in the same point: in this case QDP was able to follow the possible vessel movements along the line of sight during respiration and maneuvers. This feature was used also for PW SV repositioning and scanning plane adjustments: the probe was moved in the direction perpendicular to the scanning plane searching for the section where the QDP signal detected the highest velocities. That section was considered the optimal scanning plane of the examined vessel during longitudinal approach.

4 – Detection of refluxes in CCA and IJV. Here, the use of the DIR algorithm was particularly useful when the refluxes were small, with much slower velocity than the examined vessel main flow and near the vessel walls. In case of complete reverted flows in the IJV during expiration, the use of DIR algorithm was avoided in order to correctly follow also the fast inversions. About the evaluation of stenotic CCA, QDP was demonstrated able to show the reflux also in cases where the CD did not show any signal (as already shown regarding IJV in [11]). Both for CCA and IJV, QDP with DIR algorithm was therefore used for the direction detection of refluent blood flow and for a better visualization especially when the reflux was much smaller and slower than the main flow.

5 – Easier sampling of the blood flow signal within the examined vessel (or vessels) in case of movements of the subject due to respiration or other different origin. Especially regarding the obstetrics and cervical venous examination, the QDP, in parallel with the PW visualization (B-Mode reference used for the Multigate QDP positioning and then de-activated), enabled tracking the vessel movements and the consequent PW SV re-positioning, without the use of triplex (with its limitations in terms of lower frame rate, lower PRF limits, reduced Doppler quality).

Thanks to the above mentioned features, compared to conventional Doppler approaches, the QDP technology, with the optional DIR functionality, allows faster, easier and more reliable flow analysis in cardiac, vascular and obstetrics clinical applications.

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