Duplex Doppler Ultrasound (DDU) and Vector Flow Imaging (VFI)

The use of the ultrasounds in medical imaging was first described in 1942 and, since then, a great body of literature has been produced.(1) In order to perform an ultrasound examination a probe, or transducer, is needed. Briefly, crystals inside the transducer, when electrified, by piezoelectric influence generate a signal in form of a mechanical wave that encounters different resistances according to the material it passes through. Different tissues, thus, generate different echoes that are received by the probe itself that, by means of a computational unit, transforms echoes into images.(2) If we take advantage of the Doppler effect (3), we can study moving particles exploiting ultrasounds. The most studied tissue of the body by Duplex Doppler Ultrasound is blood. DDU can give both qualitative information, such as the direction of the blood flow, as well as quantitative information by the analysis of the Doppler spectrum, such as speed. However, several technical issues must be considered when performing a DDU examination. It is common experience that if the timeframe of a camera filming a rotating wheel is different from the speed of the wheel, the spectator will see a wheel that spins onward or backward. If the timeframe of the camera, instead, equals the speed of the wheel, the spectator will see a still image and it will seem that the wheel doesn't spin at all. Thus, the frequency at which the probe emits signals must be set accordingly to the speed of the moving object on study. In addition, in order to detect movement, the signal must reach the target at an angle different from 90 degrees, usually less than 60 degrees for best performances, otherwise the echoes generated by the moving particles will not have a different returning lag and won't give any information about the movement. The importance of the angle of incidence between the ultrasound beam and the direction of the flow is critical and can be further appreciated if we consider that the formula used to calculate the velocity of the flow is based on its cosine: $v=cf_D/2f_0(\cos\theta)$, where f_D is the shift frequency, f_0 is the emitted ultrasound frequency and θ is the angle of incidence. Thus, if the angle was 90 degrees the result of the equation would be impossible to calculate.(4)

Moreover, since blood usually flows inside the vessels in a laminar way, it has a parabolic profile with the highest speed recorded in the center of the vessel and the lowest in its periphery. Hence, the area of measurement must be set large enough in order to comprise the entire area of the vessel to measure all the different speeds of red blood cells passing through a section in a given time. This is just a short list of all the parameters that must be considered when performing a Doppler evaluation.(5) Given all these technical problems, DDU must be performed by trained operators in order to give reproducible and reliable results. By DDU several information can be collected about blood flowing in a vessel: mean velocity, flow, peak systolic velocity, end diastolic velocity, resistance index etc. and then infer their clinical correlations, for instance the presence of a significant stenosis when the velocity increases of at least 100%. Nephrology has taken advantage of DDU in a number of different clinical settings and of course in the field of hemodialysis vascular accesses.(6) However, in the efferent vein of a fistula, blood coming from an artery, does not flow in a laminar fashion, at least near the anastomosis or in venous aneurisms of long standing accesses. This accounts for the difficulties in measure blood flow inside the fistula and that's also the reason why all the fistula blood flow studies and guidelines have suggested to focus on the brachial artery rather than the efferent vein to give the most reproducible and generalizable results.(7) Turbulent flow inside the anastomosis or the efferent vein, when analyzed by color Doppler ultrasound, generates the so called aliasing phenomenon. This artifact occurs because it's inherent of Doppler modalities which utilize intermittent sampling in which an insufficient sampling rate results in an inability to record direction and velocity accurately.(8) Aliasing, even if useful sometimes in order to suspect the presence of turbulent flow when not readily apparent, usually prevents the detailed study of a vessel. To try to overcome all these DDU pitfalls and reduce the time of examination, vector imaging was developed.(9) Vector flow imaging (VFI) is a relatively novel method, which is based on different technologies. Briefly, independent firings insonate a tissue region in multiple directions; the echoes received by the transducer are coherently summed together taking into account the difference in round trip travel time from the transducer to the tissue and back, for each firing. All these information are then integrated by the graphical processing unit (GPU) of the ultrasound machine(10). There are two main systems to perform a vector flow imaging: a parallel(11) one based on plain wave emissions and a sequential one based on the transverse oscillation of ultrasound beam emitted by the transducer.(12) Thanks to the oscillating component of the ultrasound beam and the simultaneous processing of the echoes, it is possible to calculate not only the axial component of the velocity but also the transverse component, thus eliminating the insonation angle dependency and allowing a reliable graphical representation of complex blood flow patterns.(13) Vector flow imaging has been used to study carotid blood flow. It has been demonstrated that VFI was not inferior to DDU when evaluating carotid arteries but it was able to add some useful information such as the vector concetration, a quantitative index that estimate the degree of the turbulence inside the vessel.(14) Another index of turbulence that can be estimated by VFI is the mean standard deviation of the flow angles (MSTDA), also validated studying carotids.(14) MSTDA is an index of dispersion of the different vectors representing the blood flow in a vessel: the higher the MSTDA, the more turbulence with blood flowing onward, backward and in other directions different from the axial one. This kind of information cannot be obtained by conventional DDU. Moreover, the possibility to represent the blood flow by means of vectors, allows the study of blood flow components associated with an altered shear stress, a factor known to contribute to the development of atherosclerotic plaque formation and neointimal hyperplasia leading to stenosis.(15-17)

In summary, VFI did not prove superior to DDU for vascular examination but it has been demonstrated that the additional information given by VFI could be used to study in vivo, in a non-invasive way, the characteristics of regional blood flow that have been associated with the development of vascular pathology.

References

1. Brant WE, Helms CA. Fundamentals of diagnostic radiology. Philadelphia: Wolters Kluwer/Lippincott Williams & Wilkins; 2012.
2. Oglat AA, Matjafri MZ, Suardi N, Oqlat MA, Abdelrahman MA, Oqlat AA. A Review of Medical Doppler Ultrasonography of Blood Flow in General and Especially in Common Carotid Artery. J Med Ultrasound. 2018;26(1):3-13.
3. Doppler C. Uber das farbige Licht der Doppler-sterne und einiger anderer Gestirne des Himmels. Abhandl Konigl Bohm Ges Ser 2. 1843:465-82.
4. Pellett AA, Kerut EK. The Doppler equation. Echocardiography. 2004;21(2):197-8.
5. Browne JE. A review of Doppler ultrasound quality assurance protocols and test devices. Physica Medica: European Journal of Medical Physics. 2014;30(7):742-51.
6. Niyyar VD, O'Neill WC. Point-of-care ultrasound in the practice of nephrology. Kidney Int. 2018;93(5):1052-9.
7. Zamboli P, Fiorini F, D'Amelio A, Fatuzzo P, Granata A. Color Doppler ultrasound and arteriovenous fistulas for hemodialysis. Journal of Ultrasound. 2014;17(4):253-63.
8. Rubens DJ, Bhatt S, Nedelka S, Cullinan J. Doppler Artifacts and Pitfalls. Radiologic Clinics. 2006;44(6):805-35.
9. Dunmire B, M.D. KWB. Brief history of vector Doppler: SPIE; 2001.
10. Anand A. Technology White Paper Touch Prime : Advanced ultrasound imaging with an extraordinary user experience. Imaging Technology News. 2015.
11. Jensen JA, Nikolov SI, Yu AC, Garcia D. Ultrasound Vector Flow Imaging-Part II: Parallel Systems. IEEE Trans Ultrason Ferroelectr Freq Control. 2016;63(11):1722-32.
12. Jensen JA, Nikolov SI, Yu AC, Garcia D. Ultrasound Vector Flow Imaging-Part I: Sequential Systems. IEEE Trans Ultrason Ferroelectr Freq Control. 2016;63(11):1704-21.
13. Goddi A, Fanizza M, Bortolotto C, Raciti MV, Fiorina I, He X, et al. Vector flow imaging techniques: An innovative ultrasonographic technique for the study of blood flow. Journal of Clinical Ultrasound. 2017;45(9):582-8.
14. Pedersen MM, Pihl MJ, Haugaard P, Nielsen MB, Jensen JA. Quantification of complex blood flow using real-time in vivo vector flow ultrasound. Proceedings of IEEE International Ultrasonics Symposium. 2010:1088-91.
15. Malek AM, Alper SL, Izumo S. Hemodynamic Shear Stress and Its Role in Atherosclerosis. JAMA. 1999;282(21):2035-42.
16. Chistiakov DA, Orekhov AN, Bobryshev YV. Effects of shear stress on endothelial cells: go with the flow. Acta Physiologica. 2017;219(2):382-408.
17. Goudot G, Pedreira O, Poree J, Khider L, Mirault T, Julia P, et al. Assessment of wall shear stress by ultrafast vector flow imaging in carotid atheromatous stenosis. Archives of Cardiovascular Diseases Supplements. 2019;11(1):96-7.