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Invited paper

A review of Doppler ultrasound quality assurance protocols and test devices

Jacinta E. Browne

Medical Ultrasound Group, School of Physics and IEO, FOCAS Institute, Dublin Institute of Technology, Kevin Street, Dublin 8, Ireland

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ABSTRACT

In this paper, an overview of Doppler ultrasound quality assurance (QA) testing will be presented in three sections. The first section will review the different Doppler ultrasound parameters recommended by professional bodies for use in QA protocols. The second section will include an evaluation and critique of the main test devices used to assess Doppler performance, while the final section of this paper will discuss which of the wide range of test devices have been found to be most suitable for inclusion in Doppler QA programmes. Pulsed Wave Spectral Doppler, Colour Doppler Imaging QA test protocols have been recommended over the years by various professional bodies, including the UK's Institute of Physics and Engineering in Medicine (IPEM), the American Institute for Ultrasound in Medicine (AIUM), and the International Electrotechnical Commission (IEC). However, despite the existence of such recommended test protocols, very few commercial or research test devices exist which can measure the full range of both PW Doppler ultrasound and colour Doppler imaging performance parameters, particularly quality control measurements such as: (i) Doppler sensitivity (ii) colour Doppler spatial resolution (iii) colour Doppler temporal resolution (iv) colour Doppler velocity resolution (v) clutter filter performance and (vi) tissue movement artefact suppression. In this review, the merits of the various commercial and research test devices will be considered and a summary of results obtained from published studies which have made use of some of these Doppler test devices, such as the flow, string, rotating and belt phantom, will be presented.

Introduction

The importance of assessing the quality of Doppler ultrasound systems is apparent considering that the result or product of Doppler ultrasound examinations is frequently directed toward a well-defined clinical question concerning blood flow [1]. For example, Doppler ultrasound is used to determine the level of stenosis by examining the changes in blood flow in the vessel of interest, and to determine whether flow is present in a tight stenosis. Another use is to determine if changes have occurred in blood flow in transplanted kidneys [1–3]. Indeed, the use of Doppler ultrasound has become more widespread over the last decade, largely due to advances in transducer technology, digital electronics and clutter filter algorithms, with a corresponding improvement in the Doppler sensitivity, axial resolution within the sample volume and the low velocity detection capabilities of modern systems [3]. With this increasing use of Doppler ultrasound techniques, it is of paramount importance that ultrasound systems meet the requirements of each of the different clinical applications and that the quality of the information is maintained throughout the lifetime of the ultrasound system. To this end, performance and quality control tests are carried out to determine firstly that the requirements of the clinical examination are achieved at acceptance testing, and then through routine quality assurance testing to ensure that this appropriate level of performance is maintained [4]. Both the absolute performance of Doppler ultrasound and the maintenance of that performance are important [5]. The former is important given that clinicians need to know the accuracy of the maximum velocity detectability of the system, and also to know the system's detection limits in terms of the weakest Doppler signal that can be detected. For example, in the case of the accuracy of the system where the maximum peak systolic velocity is overestimated by 10% for a patient with an actual peak systolic velocity of 125 cm s^{-1} the measured velocity would be 138 cm s^{-1} which would cause this patient to be miscategorised as a >50% stenosis rather than <50% stenosis which would possibly alter the treatment regime from drug treatment to surgery [6]. Furthermore, changes in

E-mail address: jacinta.browne@dit.ie.

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Table 1
Overview of the different Doppler parameters for the Doppler modes as recommended by the two professional bodies, IPEM and AIUM.

Doppler test parameter	Professional body	Doppler mode[a]	Doppler test device
1. *Maximum velocity accuracy* – This test provides an assessment of the accuracy of the Doppler system's estimate of the maximum Doppler scatterer velocity. This is one of the most common measurements made using Doppler ultrasound and provides information concerning the degree of arterial stenosis, or of the pressure drop across cardiac valves in a patient.	IPEM, IPSM & AIUM	S	String phantom Flow phantom Rotating phantom Rotating torus phantom Belt phantom Vibrating disk phantom Oscillating thin film phantom Acoustic/electronic injection test phantom
2. *Spectral broadening* – The Doppler beam is produced by a group of elements within an array, known as the active aperture. This results in the Doppler beam insonating the vessel at a range of angles. Therefore, this leads to a spreading of the range of Doppler shift frequencies (i.e. velocities) detected by the transducer due to the beam shape rather than it being due to the blood flow itself.	IPEM, IPSM	S	String phantom Vibrating point source phantom
3. *Mean velocity estimation* – This test provides an assessment of the accuracy of the Doppler system's estimate of the mean Doppler scatterer velocity. It is also the accuracy of the colour Doppler estimate of the mean scatterer velocity. Quantitative and semi-quantitative analysis of flow in vessels is being used more frequently in the clinical setting, therefore, this requires high accuracy of velocity estimation.	IPEM, IPSM	S & C	String phantom Flow phantom Rotating phantom Rotating torus phantom Belt phantom
4. *Flow direction* – this tests the system's ability to distinguish between flow towards and away from the transducer.	IPEM, IPSM & AIUM	S & C	String phantom Flow phantom Rotating phantom Rotating torus phantom Belt phantom Acoustic/electronic injection test phantom
5. *Axial range gate* – is the extent over which the Doppler gate can detect a blood flow signal.	IPEM, IPSM	S	String phantom Flow phantom Vibrating point source phantom
6. *Sample volume registration* – measures the system's range gate sensitivity to check if it is most sensitive at the centre of the gate.	IPEM, IPSM & AIUM	S	String phantom Flow phantom Vibrating point source phantom
7. *Angle correction software accuracy* – measures the accuracy of the angle correction software of the system.	IPEM, IPSM & AIUM	S	String phantom Flow phantom
8. *Highest detectable velocity* – Highest detectable velocity is the highest velocity which it is possible to display unambiguously on the PW Doppler spectrum or the colour image. Velocities in the presence of an arterial stenosis or a cardiac valvular narrowing can reach up to 5–6 m s^{-1} and it is desirable for the Doppler mode to display these velocities without aliasing.	IPSM & AIUM	S & C	String phantom Flow phantom Rotating phantom Rotating torus phantom Belt phantom
9. *Lowest detectable velocity* – The lowest detectable velocity is the lowest velocity that it is possible to display unambiguously. Visualisation of low velocity flow is necessary in venous flow detection or in tight carotid artery stenosis to distinguish between vessel occlusion and vessel patency.	IPSM & AIUM	S & C	String phantom Flow phantom Rotating phantom Rotating torus phantom Belt phantom
10. *High-pass filter response* – This is the ability of the clutter filter to remove strong signals from the vessel wall movement, while still preserving the low velocity content of the flow signal.	IPSM & AIUM	S & C	Belt phantom Acoustic/electronic injection test phantom
11. *Penetration depth* – This is the maximum depth of a vessel in tissue from which a 50 cms^{-1} Doppler signal free of extraneous noise can be obtained, which represents a typical or average physiological velocity. In clinical practice it is often desirable to obtain signals from major vessels within the body, and also from small vessels for assessment of perfusion.	IPSM	S, C & P	Flow phantom
Sensitivity (Signal-to-Noise ratio) 12. – is the minimum detectable signal level free from extraneous noise. Sensitivity is the most important aspect of Doppler performance, since if flow cannot be detected no other aspect of performance matters.	IPSM & AIUM	PW Spectral & colour Doppler	Flow phantom Vibrating disk phantom
13. *Dynamic range* – is defined as the ratio between the maximum clutter signal and the minimum detectable flow signal while both signals are present (the clutter-to-signal ratio). Clinically, it is important to have a good dynamic range particularly for Spectral Doppler when perfusion at the arteriolar level is being measured in solid tissue, for example, in the kidneys, liver or testicles.	IPSM & AIUM	S, C & P	Acoustic/electronic injection test phantom
14. *Spatial Resolution* – This is the minimum separation in space for which two separate point or line targets can be resolved or the point spread function of a point source. Visualisation of small areas of flow is required, for example for small vessels, or for regions near to minor degrees of atheroma.	IPSM & AIUM	C & P	String phantom Flow phantom Acoustic grid phantom Rotating phantom Rotating torus phantom
15. *Temporal Resolution* – This is the minimum separation in time for which two separate events can be identified. Flow events may change very rapidly, particularly for flow in the heart, and a high frame rate is needed to follow these changes.	IPSM & AIUM	C	Rotating phantom
16. *Velocity Resolution* – This is the minimum discernible velocity difference of a colour flow image. Quantitative and semi-quantitative analysis of flow in vessels is being used more frequently in the clinical setting, therefore, which necessitates a high accuracy of velocity estimation.	IPSM	C	Rotating phantom Rotating torus phantom

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