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EDITORIAL COMMENT

The Fast and the Curious

Physiological Insights From Fast Frame Rate Imaging*

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Clinical experts in the field of noninvasive cardiovascular imaging are perpetually on the prowl for engineering solutions to medical problems. In echocardiography, technical innovations have positively impacted patient care through improvements in spatial resolution, reduction of noise, and new approaches for measuring cardiac structure and function. Innovations sometimes occur in direct response to unmet clinical needs, such as the development of 3-dimensional echocardiography to better guide procedures for structural heart disease and the advent of contrast echocardiography to better assess left ventricular dimension and function. Alternatively, new technology is sometimes introduced with somewhat vague expectations of how it should be used in routine practice, as was the case for strain echocardiography and vorticity imaging.

The major innovation described in the study by Maresca et al. (1) in this issue of *iJACC* is the detection of intramyocardial arterial blood flow, which was made possible by increasing temporal resolution by an order of magnitude compared to conventional imaging. This ultrafast form of echocardiography was achieved through plane-wave imaging, which deserves some explanation. Conventional echocardiography relies on forming a 2-dimensional image through sequential transmission of many lines that are narrowly focused by large aperture size and with phase delay of the piezoelectric elements (**Figure 1A**). With either plane-wave or divergent-beam imaging, a single beam or a few much broader unfocused beams are transmitted (**Figure 1B**), which results in much higher frame rates (2). Defocusing of the beams reduces spatial resolution which can be addressed by using advanced computer processing to localize signals based on temporal delay in returning signals (referred to by some as retrospective beamforming) and by imaging the same tissue at slightly different angles, called *coherent spatial compounding*. As a result, in the study by Maresca et al. (1), 2-dimensional datasets were acquired at around 2,000 frames/s, albeit at a rather shallow depth, which also influences frame rate.

It is self-evident that increasing temporal resolution can provide unique information such as cardiac electromechanical timing by echocardiography. In the study by Maresca et al. (1), fast frame rates enabled imaging of intramyocardial arterial and venous flow. The underlying principle is that at extremely fast frame rates, wall filters become much more efficient in removing high-amplitude, slow-moving features (3). Accordingly, the investigators were able to detect rapidly moving blood in large intramyocardial vessels, but not necessarily flow in the microcirculation, where blood velocity is much slower.

Understanding how flow in large arteries was not only visualized with ultrafast imaging but quantified is key to understanding the robustness of the approach as a potential clinical tool. The algorithm used to detect flow in this study was power Doppler imaging, which is infrequently used in cardiac ultrasound. Power Doppler relies on the measurement of pulse-to-pulse decorrelation of returning echocardiographic signals from the same location to detect moving objects. Signal is displayed according to amplitude without velocity encoding. Ordinarily, bulk blood flow, such as through vessels, is quantified by ultrasound as the product of velocity and cross-sectional area or by integrating velocity vectors over a defined area. In the study by Maresca et al. (1), the power and velocity within a region of interest was integrated over time, thereby providing an index of

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FIGURE 1 Basis for Ultrafast Echocardiography

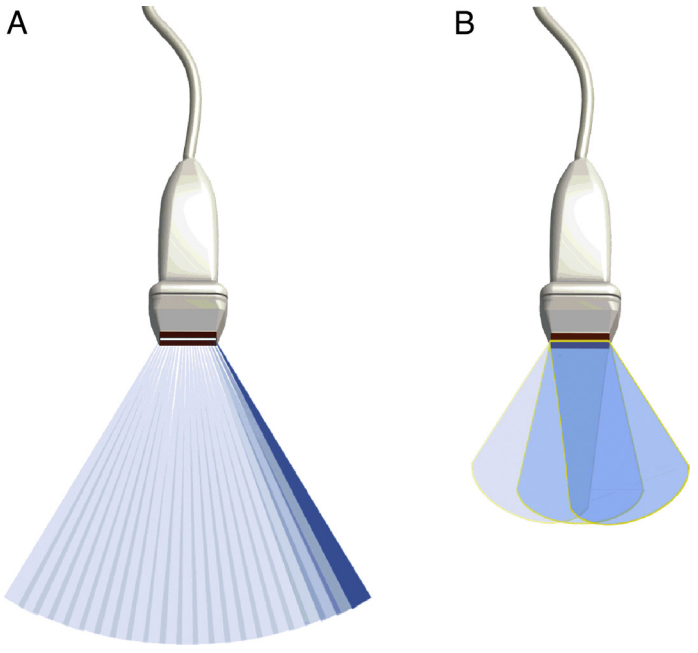

Illustration of **(A)** conventional echocardiography based on sequential transmission of highly focused lines by phased delay of piezoelectric activation and **(B)** ultrafast echocardiography with plane-wave or divergent-beam imaging, which relies on simultaneous or near-simultaneous element activation and slight angle change for coherent spatial compounding.

large vessel flow, although description of the velocity component and directionality is not provided in detail.

With the achievement of ultrafast intramyocardial vessel imaging, one now has to ask, "For what purpose?" The information provided does not address a specific unmet clinical need, which is not necessarily a negative criticism, because many important innovations in noninvasive cardiovascular imaging have had similar origins. Contextually, one could disagree with the authors' statement that large epicardial arteries are the only coronary vascular compartment that can be imaged in vivo in humans. When evaluating nutritive blood flow, it is not necessary to "resolve" microvessels. One only needs to be able to gather kinetic information that reliably reflects microvascular perfusion. Myocardial contrast echocardiography does not have a resolution of 2 to 4 μm, but it can reliably measure the concentration of 2- to 4-μm microbubbles to quantify microvascular blood volume, blood flux rate, and blood flow within the microvascular compartment (4). Similarly, magnetic resonance contrast kinetics and the perfusion-dependent uptake of radionuclide tracers are used to image flow in microvessels that are well under the detector spatial resolution limit.

Despite the widespread application of quantitative myocardial perfusion imaging, there are potential applications for imaging intramyocardial arterial flow. Again, Maresca et al. (1) are not entirely accurate when they state that the coronary intramural compartment is "uncharted." There is much known about the dynamic nature of these vessels. Since initial studies by Gregg and colleagues in 1935, it has been known that epicardial arteries are compliant, which allows their volume to expand by 20% to 40% during typical systolic pulse pressures (5,6). This knowledge, together with the observations by Chilian and Marcus (7,8) that intramyocardial arterial flow velocity becomes retrograde in early ventricular systole (**Figure 2**), indicates that backward motion of blood from intramyocardial arteries is stored in small epicardial arteries that distend and act as "capacitors" that discharge in early diastole. Key to the potential application of plane-wave imaging, relative phasic changes in flow velocity during the cardiac cycle in intramyocardial vessels were shown to be influenced by extravascular pressure (i.e., regional myocardial contractile function), intra-arterial pressure (i.e., systemic blood pressure), and various hyperemic stimuli.

In previous studies, assessment of phasic changes in intramyocardial arteries has been imaged noninvasively by specialized myocardial contrast echocardiography protocols in which transmit power is increased sufficiently to selectively destroy microbubble contrast agents in the distal microcirculation but not intramyocardial arteries (9,10). This approach provides information on left-sided phasic coronary arterial blood volume, which under normal circumstances is higher in diastole than systole. A major finding from these canine and human studies was that coronary stenosis produced an increase in coronary blood volume, especially during systole (9,10). These findings were explained by backward "milking" of an increased arteriolar blood volume that occurs from autoregulatory vasodilation (11). As a result, the systolic-to-diastolic intramyocardial blood volume ratio could be used to estimate severity of coronary stenosis without recourse to hyperemic stimulus.

In the study by Maresca et al. (1), phasic changes in intramyocardial arteries were not measured. Instead, the power-velocity integral (PVI) in diastole only was used as a "readout of myocardial perfusion." Without velocity encoding, the power signal in a single defined region is reflective of cross-sectional area (i.e., the number of scatters) (12). Accordingly, in conditions such as valve insufficiency, in which regurgitation is dictated primarily by orifice area, the power integral