Ultrasound in Med. & Biol., Vol. ■■, No. ■■, pp. ■■–■■, 2018

0301-5629/$ - see front matter

ELSEVIER

https://doi.org/10.1016/j.ultrasmedbio.2018.04.002

● *Original Contribution*

ADAPTIVE COLOR GAIN FOR VENA CONTRACTA QUANTIFICATION IN VALVULAR REGURGITATION

Pawel Kozlowski,[*,†] Alfonso Rodriguez-Molares,[‡] Thor Andreas Tangen,[*] Kjell Kristoffersen,[*] Hans Torp,[‡] Olivier Gerard,[*] and Eigil Samset[*,†,§]

[*] GE Vingmed Ultrasound, Oslo, Norway; [†] Department of Informatics, University of Oslo, Oslo, Norway; [‡] Norwegian University of Science and Technology, Trondheim, Norway; and [§] Department of Cardiology, Center for Cardiological Innovation, Oslo University Hospital, Rikshospitalet, Norway

(*Received* 25 *May* 2017; *revised* 18 *February* 2018; *in final form* 3 *April* 2018)

Abstract—Severe valvular regurgitation can lead to pulmonary hypertension, atrial fibrillation and heart failure. Vena contracta width is used to estimate the severity of the regurgitation. Parameters affecting visualization of color Doppler have a significant impact on the measurement. We propose a data-driven method for automated adjustment of color gain based on the peak power of the color Doppler signal in the vicinity of the vena contracta. A linear regression model trained on the peak power was used to predict the orifice diameter. According to our study, the color gain should be set to about 6 dB above where color Doppler data completely disappears from the image. Based on our method, orifices with reference diameters of 4, 6.5 and 8.5 mm were estimated with relative diameter errors within 18%, 12% and 14%, respectively. (E-mail: pawel.kozlowski@outlook.com) © 2018 World Federation for Ultrasound in Medicine & Biology. All rights reserved.

Key Words: **Heart valve diseases, Echocardiography, Color Doppler echocardiography, Digital signal processing.**

INTRODUCTION

Valvular regurgitation (VR) is a condition that, when left untreated, can lead to complications such as pulmonary hypertension, atrial fibrillation and heart failure. Quantification of the severity of VR is required to determine the optimal treatment for a patient. It may influence patient follow-up intervals and is an important data point for decisions regarding potential intervention.

In clinical practice, various metrics are being used to assess the severity of VR. Thavendiranathan et al. (2012) reported a few of them: effective regurgitant orifice area measured by proximal isovelocity surface area; regurgitant volume and regurgitant fraction measured by calculating the difference between inflow and outflow stroke volumes; and vena contracta (VC) width, which is the width of the narrowest portion of a regurgitant jet. Nishimura et al. (2014) emphasized that grading of VR severity is complicated and should be based on integration of multiple hemodynamic parameters measured by Doppler echocardiography, rather than just a single parameter. They recommend performing several different measurements and comparing them with defined-in-clinical-practice "triggering values." Once one of the triggers is reached, the patient should be considered for surgery.

Quantification of VR after interventions to reduce regurgitation, such as percutanous mitral valve repair, is also increasingly important clinically. Foster et al. (2007) measured VC diameter, regurgitant volume, regurgitant fraction and effective regurgitant orifice area with relatively low reproducibility of the VC diameter.

Yoganathan et al. (1988) stated that the location of the VC depends on the nature of the orifice causing regurgitation and is independent of flow rate. They also asserted that the VC can be found at, or in close vicinity of, a smooth orifice. In the case of a sharp-edged orifice, VC is just downstream of the orifice. Furthermore, the size of a regurgitant jet increases with the size of VC and is relatively independent of flow rate (Little et al. 2008).

Measurement of VC width is performed with 2-D color Doppler echocardiography in a slice aligned with the long axis of the jet (Thavendiranathan et al. 2012). Biner et al. (2010) found that the inter-observer agreement for grading mitral regurgitation (MR) as severe and non-severe

Address correspondence to: Pawel Kozlowski, Department of Informatics, University of Oslo, Oslo, Norway. E-mail: pawel.kozlowski@outlook.com

based on VC width is suboptimal. This was the first multicenter study where 18 cardiologists at 11 different institutions manually measured VC width. Inter-observer agreement on the severity of MR was only fair. Raw agreement and κ coefficients were 75 ± 15% and 0.28 (95% confidence interval [CI]: 0.11–0.45), respectively. What is more, technical parameters are not standardized between studies and vendors. Thus, different settings of parameters like color gain, arbitration, wall filter, depth and sector size can lead to under- or overestimation of VC measurements (Maragiannis and Little 2013). Automatic adjustment of these parameters could be an important aid in performing VC measurements. It would simplify the workflow and allow for more reproducible quantification results, and that, in turn, could make VC a more robust indicator of VR severity.

The purpose of this study was to optimize selection of the color gain parameter during VC measurement. Many studies recommend keeping the color gain at its maximum just below where random noise develops (Hyodo et al. 2012; Shanks et al. 2010; Thavendiranathan et al. 2012; Yosefy et al. 2009; Zeng et al. 2011). This introduces the blooming artifact, and care must be taken to measure only the highest velocities within the visible color Doppler signal (Zoghbi et al. 2017). The primary goal of automatic optimization of color gain is to eliminate this artifact, thus revealing the true extent of the jet core. This will eliminate user variability with respect to color gain and shows promise in increasing the overall reproducibility of grading VR. The reproducibility of VR is influenced by several factors (*e.g.,* image quality, filling pressure, probe-to-jet angle) that need to be taken into account. A study of all these factors was beyond the scope of this article. To achieve our goal, color Doppler data of jets with known orifice diameters were acquired. The optimal color gain was found based on a linear regression model evaluated on a subset of the acquired data. The remaining data were used for verification of the model.

METHODS

We built a phantom to produce controlled flow jets and acquired 2-D image sequences of the flow with the Vivid E95 cardiovascular ultrasound system (GE Healthcare, Horten, Norway) equipped with the 4V transthoracic probe. The scanning sector included the orifice, the VC and the downstream jet, and was aligned with the long axis of the jet.

The parameters of interest were color gain, peak color Doppler signal power in the vicinity of the VC and flow velocity. To compute peak power, raw color flow data were harvested right after the flow parameter estimation stage (Ferrara and DeAngelis 1997). These data included the power of the Doppler signal. To increase the number of

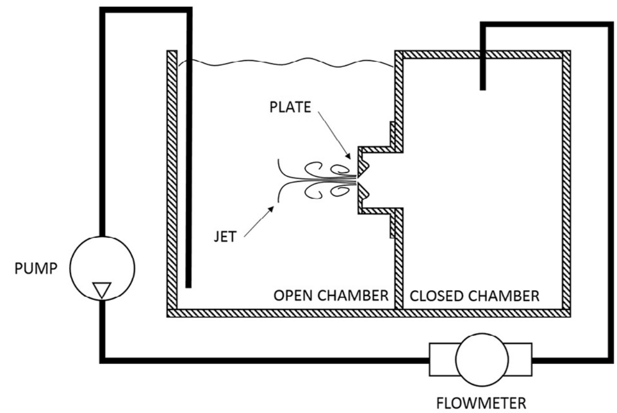

Fig. 1. Schematic of the *in vitro* setup used to re-create the jet.

data sets in the experiment and to obtain a wider range of signal-to-noise ratio (SNR), artificial noise was introduced in a post-processing step.

Jet phantom

A jet phantom composed of two chambers, one open and one closed, was designed (Fig. 1). Between the chambers was a frame allowing us to mount a plate with an orifice that connected both chambers. The two chambers were filled with a 0.01% weight suspension of Sephadex G-25 (Sigma-Aldrich, St. Louis, MO, USA) in de-ionized water. The closed chamber was pressurized with a computer-controlled centrifugal pump (RS Pro, RS Components Ltd., Northants, UK), and the open chamber was kept at atmospheric pressure. Because of the pressure difference, a jet was produced in the open chamber. The flow rate was monitored using a turbine flowmeter (RS Pro, RS Components Ltd.), which was calibrated in-house.

Three plates made of acrylonitrile butadiene styrene (ABS) were 3-D printed through fused deposition modeling (Lulzbot, Aleph Objects Inc., Loveland, CO, USA). The ABS plates were designed with orifices 4, 6.5 and 8.5 mm in diameter to represent clinically relevant, moderate and severe regurgitation (Zoghbi et al. 2017). A profile was designed to induce a 45° flow angle at the edges of the orifice. Figure 2 is a photograph of the three ABS plates used.

For each plate, data were acquired at different flow rates. Table 1 summarizes flow rates and flow velocities in acquired data sets, grouped by orifice size.

Noise level modification

The signal power from the raw color flow data P_{dB} was given in logarithmic scale. It was then converted to linear scale using

$$P = 10^{\frac{P_{dB}}{10}} \quad (1)$$