Published in final edited form as:

J Ultrasound Med. 2019 July ; 38(7): 1875–1885. doi:10.1002/jum.14859.

A Real-Time Color Doppler Marker for Echocardiographic Guidance of Acoustically Active Extracorporeal Membrane Oxygenation (ECMO) Cannula

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Summary

Ultrasound B-mode imaging guidance of cannulas can be compromised by noise, artifacts, and echogenicity not distinctive from that of surrounding anatomy. We demonstrate that color Doppler echocardiography can guide a venovenous (VV) extracorporeal membrane oxygenation (ECMO) cannula by individual color markers that identify each of its 3 ports. The VV ECMO cannula is made acoustically active by embedding piezoelectric crystals into the ports. Each crystal vibrates and acoustically interacts with a Doppler imaging signal. The interaction generates a Doppler shift and produces instantaneous color markers that guide positioning of the cannula within the right atrium and vena cava.

Keywords

acoustically active catheter; color Doppler guidance; minimally invasive interventions; ultrasound imaging guidance

INTRODUCTION

With the advent of minimally invasive interventions, ultrasonography has become a method of choice for imaging guidance of intracardiac and intravascular instruments such as catheters, needles, and cannulas. Practical examples of minimally invasive cardiovascular interventions include transcatheter treatment of valvular heart disease^{1, 2} and myocardial cellular therapy delivered by transendocardial injections.³ However, image noise and artifacts in grayscale (B-mode) scans make navigation of minimally invasive imaging tools difficult. In addition, echogenicity of cardiovascular tissue and minimally invasive tools are often similar in B-mode scans. Hence, the tool appearance could falsely mimic an anatomic structure and vice versa. Therefore, identification of minimally invasive tools inside the cardiovascular system by ultrasonography must be clear-cut, and spatial tracking during insertion and manipulation instantaneous.

In previous publications, we introduced novel application of both pulsed-wave⁴ and color^{5, 6} Doppler echocardiography for real-time tracking of an acoustically active intracardiac catheter. We discussed in detail alternative ultrasound imaging methods for navigation of minimally invasive interventions.^{5, 6} Investigators have developed numerous approaches in which hardware or software of an ultrasound machine was modified to display a real-time spot marker for spatial navigation of minimally invasive instruments.⁷⁻¹¹ Similar to some of those approaches, the present method makes use of a vibrating piezoelectric crystal, which acts as an acoustic beacon. Unlike other approaches, we employ an unmodified, routinely available color Doppler echocardiography machine. There is no electronic connection of the echocardiography machine with a waveform generator to drive vibrations of the crystal.

Extracorporeal membrane oxygenation (ECMO) maintains gas exchange, blood perfusion, and systemic circulation via large cannulas placed in central vessels. We present innovative acoustic navigation of a venovenous (VV) ECMO cannula by using conventional color Doppler echocardiography. We chose the VV ECMO cannula for our experimental tests because the cannula comprises 3 ports that are not routinely identifiable by B-mode scans. Still, optimal placement of the cannula within the cardiovascular system is critical for its simultaneous blood drainage and delivery functions. We have embedded a miniature piezoelectric crystal into each of the 3 ports. Each crystal produces an acoustic signal and can be set to generate a unique color marker for real-time spatial guidance by Doppler echocardiography.

In this paper, we present acoustic navigation of the VV ECMO cannula in testing conditions ranging from “optimal” scans in degassed water, to “realistic” scans in an open-chest beating pig heart, to highly challenging “limited” scans obtained by transthoracic imaging in a closed-chest pig.

MATERIALS AND METHODS

Acoustically Active VV ECMO Cannula

The VV ECMO cannula (Figure 1) has 2 separate lumens. One lumen is connected with the proximal and distal ports for venous blood drainage from the superior vena cava (SVC) and

inferior (IVC) vena cava, respectively. The other lumen is connected to the middle port and delivers oxygenated blood into the right atrium (RA). We have made the 3 ports on the VV cannula acoustically active by installing round, omnidirectional piezoelectric crystals 1 to 3 mm in diameter. The crystals are embedded and glued to the cannula in such a way that patency of each port is preserved. Up to 2 crystals at a time can be connected to a 2-channel waveform generator (Agilent 33500B; Agilent Technologies, Loveland, CO, USA) with a 33- to 42-gauge double-conductor stranded wire and continuously driven by a square-wave signal with 100 to 103 kHz frequency and 0.3 to 3.0 peak-to-peak voltage (Vpp).

Echocardiography Scans

A Vivid 7 (GE Healthcare, Milwaukee, WI, USA) ultrasound system and an M4S phased array sector probe (GE Healthcare) were set to harmonic B-mode imaging at 1.7/3.4 MHz or 2.15/4.30 (transmit/receive) frequencies. In color Doppler settings, we used transmit frequencies between 1.9 and 2.8 MHz and a gain setting between -20 and -17 dB. The negative gain setting desirably minimized or eliminated imaging of blood flow patterns in vivo while preserving display of the color Doppler marker. The Doppler color velocity scale ranged from ± 61 to ± 90 cm/s, and a conventional red/orange and blue/cyan color map was used during acquisition.

Digitally recorded echocardiography scans have been transferred in a DICOM format to a computer with EchoPAC software (GE Healthcare) and converted to a video format. This software also allows for offline adjustments of the Doppler color map and color velocity scale. We used this feature to make the color markers for the distal, middle, and proximal ports blue, red, and yellow, respectively, for consistency of appearance in different experimental settings presented in Figures 2 through 4.

Experimental Settings

We tested the color Doppler marker in 3 different experimental settings: 1) in vitro in a water container, which represented optimal scanning conditions; 2) in vivo in an open-chest pig, which simulated realistic clinical scanning conditions; and 3) in vivo in a closed-chest pig, which replicated limited transthoracic clinical scans. The animal studies were approved by the Mayo Institutional Animal Care and Use Committee.

The ECMO cannula was placed in a 3-gallon container padded with a sound-absorbing layer and filled with degassed water. During image acquisition, the cannula ports were subsequently centered within a 14-cm-deep sector scanning field.

The open-chest study was performed in a pig weighing 80 kg. The animal was intubated, mechanically ventilated (Narkomed 6000; Draeger Inc, Telford, PA, USA), fully anesthetized with inhalation isoflurane and intravenous fentanyl, and placed in the supine position. The chest of this animal was open by mid-sternotomy and the heart placed on a pericardial cradle. An attenuated urethane pad was interposed between the transducer face and epicardial surface during ultrasound scans. The interposed urethane pad induced an approximately 8-dB signal loss and mimicked ultrasound signal attenuation caused by a human chest during clinical echocardiographic studies.¹²

The closed-chest study was performed in a pig weighing 87 kg. The animal was intubated, ventilated, and anesthetized as described above. We employed transthoracic parasternal or atypical echocardiographic projections for obtaining views of the RA and the adjacent segments of the IVC and SVC. Transthoracic scans in an adult pig are technically difficult and of poor imaging quality due to narrow intercostal spaces and oval configuration of the chest.¹³ Ultrasound gel was used in both animal studies to assure acoustic coupling of the transducer.

Instantaneous Color Doppler Marker

The VV ECMO cannula is inserted through the right jugular vein. The insertion is guided by B-mode imaging combined with color Doppler imaging, producing an instantaneous marker for identification of each of the 3 cannula ports as needed. The color Doppler marker is generated as follows: Each crystal embedded into the ECMO cannula (Figure 1) can be individually connected to the waveform generator to vibrate and produce an acoustic field containing high-frequency harmonics. The harmonics interact with the transmitted Doppler imaging signal. This interaction results in a new signal that is received by the echocardiography system and interpreted as a Doppler shift. Consequently, an instantaneous color marker is displayed on the ultrasound system screen (Figures 2–4). This marker tracks a position of the vibrating crystal within a color Doppler scan plane and identifies the specific port to which the crystal is attached on the VV ECMO cannula. Changes in the driving signal frequency or color velocity scale and map settings determine the color of the marker, which can then be made unique for each identified port.

RESULTS

In Vitro Setting in Water

Figure 2 shows the distal, middle, and proximal ports on the VV ECMO cannula in B-mode imaging (left panels) and in color Doppler mode imaging with the color marker active (right panels) under optimal scanning conditions. Combinations of the driving frequency at 101 or 103 kHz with a color scale set to ± 70 or ± 90 cm/s produced Doppler markers with red, blue, and yellow colors that distinctly identified the distal, middle, and proximal ports, respectively. The locations of individual ports would not be identifiable in conventional B-mode scans. The Doppler gain setting of -20 dB made these in vitro results consistent with in vivo studies, in which the negative gain was used to avoid displaying color patterns of blood flow. Even with a reduced Doppler gain, amplitude of only 0.3 or 0.4 Vpp was needed to drive the embedded crystals and produce clearly visible markers.

In Vivo Open-Chest Setting

The open-chest epicardial scans in a pig with an interposed attenuating pad were comparable in imaging quality to human clinical transthoracic echocardiography scans. Figure 3 shows scans obtained by B-mode (left panels) and color Doppler (right panels). Identification of the cannula tip, where the distal port is located, is straightforward. However, the blue marker pinpoints the exact location of the distal port on the cannula tip. Moreover, the presence of the marker guarantees that the depicted cannula tip is real (a false tip can occur in partially out-of-plane position of the cannula). The middle and proximal ports are not identifiable in

the B-mode scans. We used red and yellow markers to identify and optimize position of those ports in the RA and SVC, respectively.

The color Doppler scans in Figure 3 (right panels) match both the size and shape of the underlying B-mode images. Therefore, a full length of the marker along the interrogating Doppler beam is displayed. For comparison, color Doppler scans in Figures 2 and 4 (right panels) approximate more closely the location of the cannula. As a result, the Doppler scan size is smaller and, therefore, the elongated color markers appear shorter and are centered across the cannula at the location of the particular port.

In Vivo Closed-Chest Setting

Figure 4 demonstrates B-mode (left panels) and color Doppler (right panels) images obtained by transthoracic scans in pigs. The resulting scans expectably are of poor quality, which simulates limited-quality scans in humans. The ECMO cannula is barely recognizable in B-mode scans, and the distal port had to be approximated. Consequently, the role of the color Doppler markers for each port becomes 2-fold. First, the mere occurrence of the marker indicates the presence of the corresponding port within the Doppler scan plane. Second, the marker guides the particular port identified within the scan plane to the appropriate anatomic location. The Doppler gain was set to -15 to -20 dB for consistency with open-chest studies and scans in water. The driving signal amplitude ranged from 2.0 to 9.0 Vpp.

DISCUSSION

In this experimental study, we demonstrate that an acoustically active VV ECMO cannula can be guided by conventional color Doppler echocardiography under optimal, clinically realistic, and limited imaging conditions. Display of an instantaneous color Doppler marker enables straightforward identification of each of the 3 ports on the VV ECMO cannula and their real-time tracking for optimal placement within cardiovascular anatomy.

In its conventional application, color Doppler echocardiography identifies motion direction of the myocardium (ie, tissue Doppler imaging) or blood (ie, flow Doppler imaging), and measures mean and variance of tissue or blood velocity. Such measurements are presented as color-coded velocity maps that are superimposed, in real time, over B-mode scans.

In our new application, color Doppler imaging is employed as a guidance method. The ability of an ultrasound system to simultaneously generate B-mode and color Doppler images is unaffected, and any color flow Doppler-capable ultrasound machine can be used for our guidance approach. During image guidance, visualization of color-coded blood flow velocities is subdued by decreasing the Doppler gain, so that only the color marker identification and tracking of the specific port on the VV ECMO cannula is displayed. However, if so desired, blood flow velocity imaging can be restored within the same scanning projection immediately by increasing the Doppler gain back to its conventional level. Combining color Doppler flow and guidance scans could be useful for assurance of preserved intravascular blood flow and optimal positioning of the ECMO cannula, respectively. We specifically used the VV ECMO cannula (Figure 1) in our tests because of

its relative complexity (2 lumens and 3 ports for blood drainage and delivery). This complexity translated into challenges in port identification and guidance by B-mode scans and documented the practical functionality and benefits of the instantaneous color Doppler markers.

Even under optimal scanning conditions in water (Figure 2), plain B-mode imaging did not allow for visual localization of the ports on the cannula, although their identification and optimal placement are critically important due to the different functional roles of the ports (ie, blood drainage vs delivery). Moreover, if the tip or the body of the cannula visually merged with its surroundings due to similar echogenicity, neither would be distinguishable and proper spatial guidance practically impossible or very unreliable. Activating only 1 crystal at a time or using a unique marker color allows for easy identification of a specific port.

In animal studies, we tested generation of the color marker and its role in clinically realistic scanning conditions (Figure 3) and in highly challenging limited imaging conditions (Figure 4). The role of the marker was critical in both conditions for identification of the related distal, middle, or proximal port. In the limited conditions, poor depiction of the cannula in B-mode scans would preclude even determination of whether the cannula is within the scan plane or not. Out-of-plane motion of the cannula due to cardiac or respiratory cycling was present but immediately noticeable by the color marker vanishing from the displayed projection of the heart or vessel. We typically activated only 1 piezoelectric crystal at a time to display an instantaneous marker for the specific port on the VV ECMO cannula. However, with the available 2-channel waveform generator, we had the ability to engage 2 different crystals at a time and, thus, display 2 specific markers with distinctive colors within 1 scan plane. These strategies eliminated any potential difficulty with identifying the specific port even in limited-quality transthoracic scans in our experimental pigs.

Notably, the signal amplitude in closed-chest studies (Figure 4) was approximately 10 times higher than open-chest scans conducted with an interposed attenuating pad (Figure 3). The higher signal amplitude in the closed-chest studies was demanded by the loss of signal through the pig chest. The Doppler gain was set to -15 to -20 dB in closed-chest scans for procedural consistency. Adjusting the gain to less negative or even to positive values during closed-chest scans would considerably enhance the markers and, consequently, allow for the use of lower voltages for driving embedded crystals. However, flow patterns in the IVC, SVC, and RA would then occur and visually mask the markers. Online or offline changes in the color map and color velocity scale in Doppler scans, along with adjustments in frequency of the crystal-driving signal, allowed for customization of the instantaneous marker color. This was practical considering that 3 different ports on the same cannula needed to be individually identified and guided in our study.

The limitation of the instantaneous marker is that it appears as an elongated color pattern of varying length (defined by the size of the color Doppler scan) and is always directed along the Doppler beam interrogating the vibrating crystal. The elongated marker alone cannot identify the exact location of the port. Instead, it identifies the port in B-mode images by crossing depiction of the cannula at location of the port. Therefore, at least a limited

visualization of the cannula by B-mode imaging is required. We speculate, however, that a completely lacking B-mode display of the cannula in poor-quality scans would likely be accompanied by a sparse or lacking depiction of the surrounding cardiovascular anatomy. Under such extremely limited imaging conditions, imaging would be impractical, and spatial guidance within cardiovascular anatomy would not be possible anyway.

The advantage of our guidance method is that it opens up a new use for broadly available conventional color Doppler echocardiography machines as spatial navigation tools, since no hardware or software modifications are needed. Moreover, the color marker displayed by the color Doppler machine is robust in identifying a particular port and tracking its location in all tested imaging conditions.

Our present study demonstrates that each instantaneous color Doppler marker produced by 1 of the piezoelectric crystals embedded in the acoustically active VV ECMO cannula serves at least 3 purposes. First, a sole occurrence of the marker on the echocardiography screen alerts users that the vibrating crystal (and thus the related port) is located within the imaging scan plane. This turned out to be especially useful in limited-quality scans. Second, the marker identifies the specific port of the VV ECMO cannula. Finally, the color marker allows for real-time guidance of the particular port toward its optimal anatomic position.

CONCLUSIONS

Acoustic interactions of an embedded vibrating crystal with an interrogating Doppler beam produce an instantaneous color marker that is robust even under limited echocardiographic scanning conditions. In the current experimental setting, the marker distinctly identified drainage and delivery ports of the acoustically active VV ECMO cannula and guided them reliably to their desired anatomic locations. The presented method is expected to open up a new role for color Doppler ultrasonography as an imaging guidance technique and translate into the development of a variety of acoustically active tools for ultrasound-guided minimally invasive interventions.

ACKNOWLEDGMENTS

We thank Naomi M. Gades, DVM, MS, for veterinary assistance. This work was supported by the R01 grant EB019947 from the National Institutes of Health. The contents of the study are solely the responsibility of the authors and do not necessarily represent the official views of the National Institutes of Health.

Abbreviations:

ECMO	extracorporeal membrane oxygenation
IVC	inferior vena cava
RA	right atrium
SVC	superior vena cava
V_{pp}	peak-to-peak voltage
VV	venovenous

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Figure 1. Acoustically active VV ECMO cannula with connectors to distal, middle, and proximal crystals (**top panel**). Magnified photo (**bottom panel**) shows locations of the distal, middle, and proximal ports with embedded piezoelectric crystals.

Figure 2.

Acoustically active ECMO cannula scanned under optimal imaging conditions. Unlike B-mode scans (**left panels**), color Doppler scans (**right panels**) unambiguously identify individual locations of the distal, middle, and proximal ports (**top, middle, and bottom panels**, respectively).

Figure 3. Acoustically active ECMO cannula scanned under simulated clinical imaging conditions. The cannula is easily recognizable in the B-mode scans (**left panels**). However, the instantaneous Doppler markers (**right panels**), which are made color-specific for each indicated port, are required to properly place the ports within the cardiovascular anatomy (**top, middle, and bottom panels**).

Figure 4.

Acoustically active ECMO cannula scanned under simulated limited imaging conditions. The cannula is poorly recognizable in B-mode scans (**left panels**) and, consequently, the role of each instantaneous Doppler marker (**right panels**) in identification and guidance of the ports is critically important.