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Flow model with vessel tree for segmentation and registration with color Doppler ultrasound and CT

Christian Winter, Tobias Bergen, Sophie Krüger and Michael Lell

Abstract— **Numerous phantoms for human organs are commercially available or designed for scientific purposes. None of these combine the imaging possibility with color Doppler ultrasound (CDU) and computer tomography (CT) while providing vessel branches with bifurcations as natural landmarks.**

We designed, built and evaluated a flow model with vessel tree which can be imaged with CDU and CT. It aims at development and reproducible evaluation of segmentation and registration work under realistic conditions. The colored representation of vessels in CDU compared to grayscaled representation in B-Mode simplifies and stabilizes the necessary segmentation process. The used tube construct with several bifurcations represents a simplified vessel tree and can be operated with various blood mimicking fluids.

The usability and practical value of the model with respect to flow characteristics and visibility of bifurcations were tested and confirmed in experiments with state-of-the-art CDU and CT equipment.

I. INTRODUCTION

Ultrasound is a very popular modality to scan and examine tissues and structures of organs without invasive procedure, radio frequency or harmful after effects. As the time of application is not limited, ultrasound is the preferred technique for live imaging of organs like liver and bladder. Several research groups work on robust registration of ultrasound volume data with preoperative computer tomography (CT) data. The intention is to overlay important information over (tracked) live image data. A trend-setting approach is to register natural landmarks like the tips and bifurcations of vessel trees [1], [2]. As long as the registration algorithm is provided with a sufficient number of prominent features and the detection of these features is fast and robust, a correlation between different modalities like CT and ultrasound is possible. Provided that CT data is combined with preoperative planning data, surgery can be assisted by augmenting the updated ultrasound data. The highlight of such approaches is the adaptability to organ motion and tissue deformation.

Development and evaluation of algorithms for vessel segmentation and registration depend on realistic models or real data. The latter is barely suitable to reproduce experimental results over time. Therefore, we introduce a flow model with vessel tree for color Doppler ultrasound (CDU) and CT. This model replicates the human liver, has realistic look-and-feel and combines the following features:

- Vessel tree with branches visible in CDU for quick color-based segmentation of bifurcations
- Tissue with realistic scattering properties
- Tube construct visible in CT scan
- Soft materials both for tissue and tubes, allowing authentic probe manipulation
- Flow components simulating volume and speed of the cardiovascular system

There are numerous publications about ultrasound models and many products are commercially available. Several companies fabricate organ phantoms for educational purposes, some of which contain tumor substitutes for ultrasound training. All of them are static and do not provide flow for CDU. Another class of technical phantoms include Doppler functionalities but do not replicate human organs. Hoskins et al. [3] describe a flow model for the generation of physiological Doppler waveforms. They use a suspension of scattering particles and a pump with a microcomputer controlled stepping motor to simulate Doppler data in the linear sections of one single tube. The study is similar to the evaluation described by Sjoblom [4] in his patent about an ultrasonic Doppler flow phantom with several independent flow paths. In [5], Hein et al. introduce the design of a flexible blood flow phantom which allows generation of predictable flow profiles and takes into account blood pressure, different vessel sizes and different attenuating media. Although most of the phantoms provide realistic blood flow simulation and Doppler waveform, there is no approach representing a vessel tree by means of a tube construct with bifurcation.

Besides scattering characteristics, the design of a blood flow model has to consider velocity and blood pressure. Blood circulates at different velocities through the cardiovascular system. Volume and speed depend on the blood pressure, the type and diameter of the vessel and fluid characteristics. Blood velocity varies from around $0.03\frac{\text{cm}}{\text{sec}}$ in tiny capillaries up to $20\frac{\text{cm}}{\text{sec}}$ or even $50\frac{\text{cm}}{\text{sec}}$ in the aorta and major arteries.

Normal blood pressure in a healthy adult (with low physical activity) ranges between 80mmHg in the heart filling phase (diastolic) and 120mmHg in the cardiac ejection phase (systolic). Blood flow can be visualized by the use of CDU and measured by color duplex ultrasound (CDxU). The early work of Angelsen [6] presents a theoretical study of the scattering of ultrasound from blood. The main results are:

1) Blood behaves essentially as a continuum.

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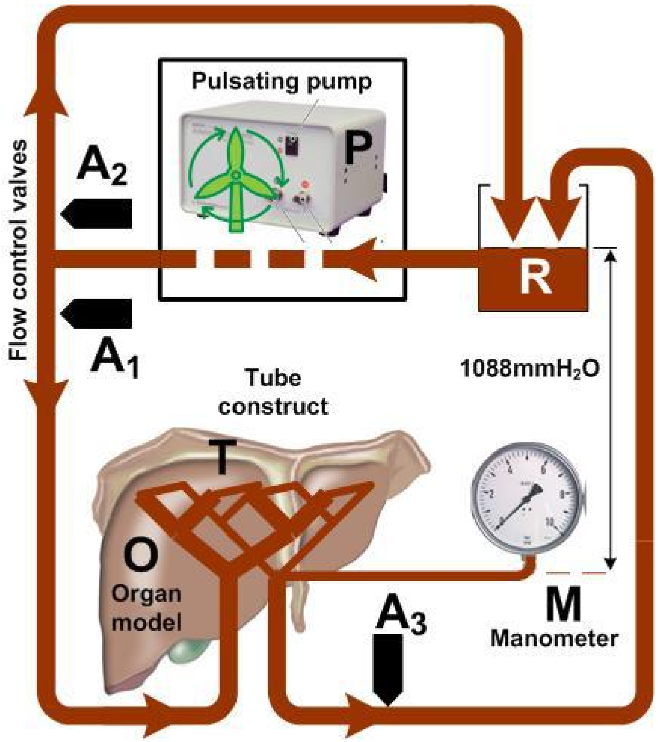


Fig. 1. Schematic design of the proposed phantom: The pulsating pump (P) circulates blood mimicking fluid from the reservoir (R) through the tube construct (T) in the organ model (O). The bypass pipe together with the manometer (M) and the valves (A_1 to A_2) allow for adjusting the flow characteristics in the model.

2) The scattering arises mainly from the red cells (erythrocytes) which have a size of $5\mu m$ to $7\mu m$ and by far outnumber the rest of the formed elements, both in quantity and volume.

II. METHODS

To realize the required features of the model we incorporated the following design (cp. Fig. 1): A pulsating pump (P) circulates blood mimicking fluid from a reservoir (R) through the tube construct (T) in a special organ model (O). By means of a manometer (M) and three valves (A_1 to A_3), one at a bypass pipe, it is possible to adjust the correct pressure and speed in the tube construct.

A. Tube construct as simplified vessel tree

In the introduction, we pointed out the need for bifurcations as natural landmarks in the simulated organ for the purpose of registration in several modalities. In our case, the precise diameter and course of the vessel tree do not matter. We designed this simplified vessel tree with soft polyvinyl chloride tubes, six Y-shaped bifurcations and eight elbow elements. Fig. 2 depicts the manufactured vessel tree with marked bifurcations B_1 to B_6. All tubes and bifurcations are 4mm in inner diameter and the eight elbows reduce the diameter by 1mm. The elbows prevent bending and rudimentarily meet the demand for ramification in the outer branches.

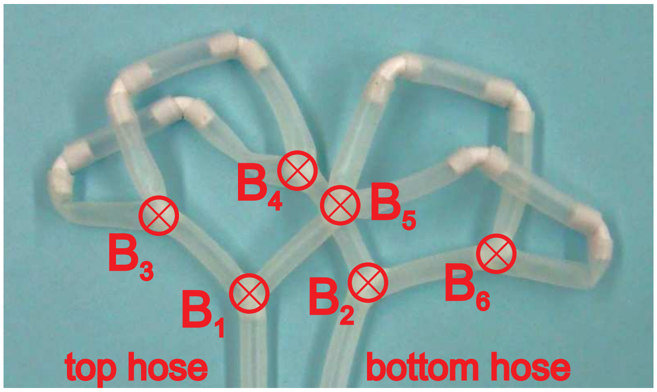


Fig. 2. Tube construct with six Y-shaped bifurcations as simplified model for vessel tree in human liver.

B. Organ model for CDU and CT

KYOTOKAGAKU embedded the tube construct as depicted in Fig. 2 into a soft silicon like material (Japanese Patent No. 3650096). Two hoses serve as connectors to the vessel system. The shape of the model is chosen to replicate the human liver and can be placed in a water filled basin (cp. Fig. 3) or a real-sized body phantom. The liver model is based on *IOUSFAN* offered by KYOTOKAGAKU as static abdominal intraoperative and laparoscopic ultrasound phantom with built-in tumors. The look-and-feel and the scattering properties show realistic behavior with respect to US probe manipulation and organ deformation, also affecting the internal tube construct. Because of the comparable hounsfield scale of the patented material, the model can also be imaged by CT. Particularly the tube construct with its bifurcations can be perfectly detected and segmented. The long-life material makes the phantom durable especially when compared to cadaver organs.

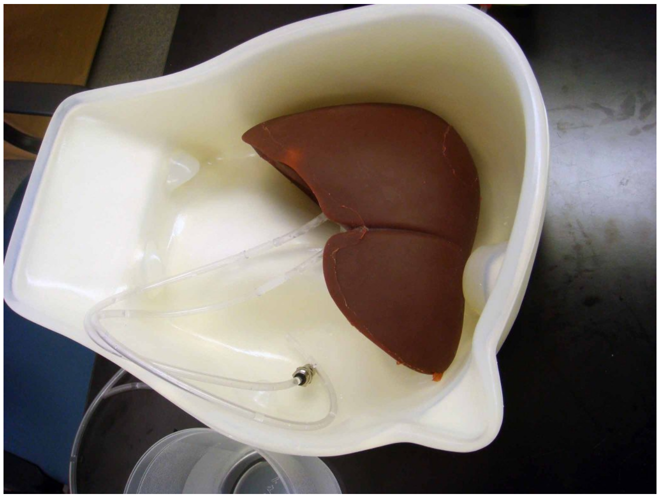


Fig. 3. Liver replica with embedded tube construct and two connecting hoses. Water filled basin as storage box.

C. *Pulsating pump and flow control with bypass and valves*

To simulate the pulsating blood flow, we used a pump with a lifting cylinder and one-way valves driven by a continuously rotating motor. This concept imitates the heart's function most naturally. Normally the cardiac output in the human body is between $4\frac{\text{l}}{\text{min}}$ and $5\frac{\text{l}}{\text{min}}$, where approximately $1\frac{\text{l}}{\text{min}}$ flows through the portal vein and $0.5\frac{\text{l}}{\text{min}}$ flows through the hepatic artery. Within the phantom, the volume per time depends on the size of the cylinder and on the frequency of cycles. The speed of blood depends on several factors like the size of the vessel, its distance and orientation to the heart and other characteristics like composition and fluid dynamics. The volume per time flowing through the tube construct is controlled by the ratio A_1/A_2, denoting the areas of the profiles of the two valves of the same name (cp. Fig. 1). The redundant portion is led back to the reservoir via the bypass pipeline. The lower pressure in the tube construct has to equal the diastolic reading of 80mmHg. This equals the pressure exerted by a column of mercury 80mm high with a density of $13.6\frac{\text{g}}{\text{cm}^3}$ under the standard acceleration of gravity. We substitute the mercury column by a difference of level between the reservoir and the organ model of

$$80\text{mmHg}\cdot 13.6\frac{\text{mmH}_2\text{O}}{\text{mmHg}} = 1088\text{mmH}_2\text{O}.$$

The systolic pressure peak depends on the pump characteristics, the tube profile and the regulation of the valve A_3 at the exit of the tube construct. For calibration and monitoring the manometer M is connected right at the exit of the organ model in front of the valve.

D. *Blood mimicking fluid for experiments*

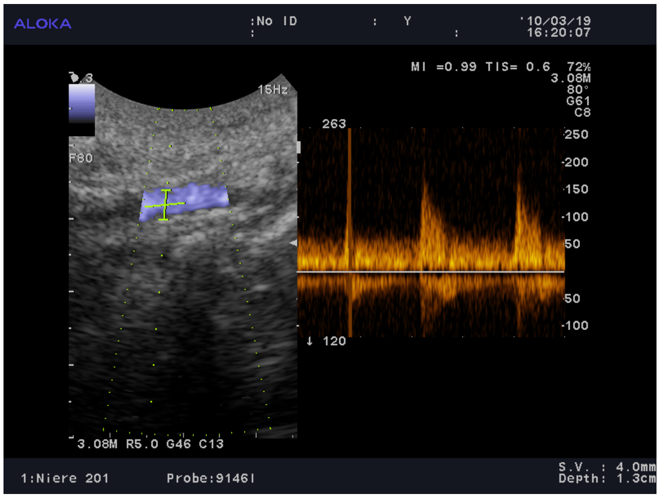
If a phantom is to produce Doppler US spectral waveforms similar to those obtained with blood in vivo it is necessary to use a blood mimicking fluid (BMF) consisting of ultrasound scattering particles suspended in a fluid. Various BMFs based on Sephadex, nylon, starch, polystyrene micro spheres, cellulose pulver and other additives or micro bubbles have been described in literature. See [7] for a detailed review. We use Sephadex G-10 or commercially available flour, which is a cheap alternative to easily mix a long-term stable suspension. In Sec. III-B we show the sufficient scattering characteristics of the suspension when used as BMF with our phantom.

III. EXPERIMENTS, RESULTS & DISCUSSION

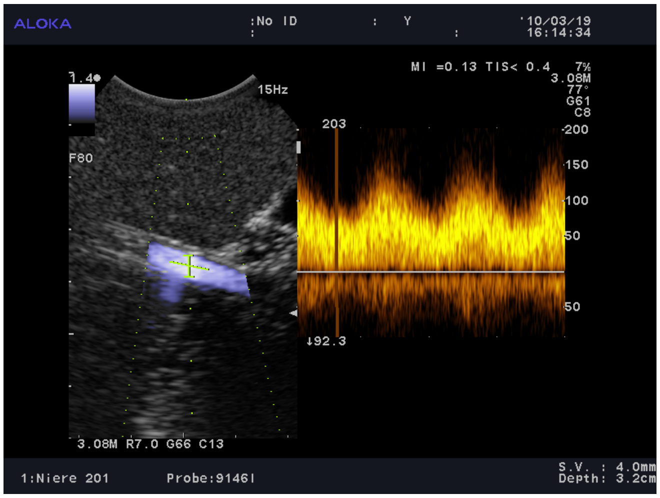
A. *Ultrasound and CT equipment*

We used an ALOKA ProSound Alpha 7 ultrasound system with an intraoperative convex shaped multi frequency probe at 3MHz. The special probe was applied due to the intended intraoperative application (cp. Sec. I). The Alpha 7 offers a high-definition blood flow imaging mode called *eFlow*. Compared to conventional Color Flow and Power Flow, the spatial resolution is higher and blood vessels are less bloomed or merged. Snapshots and image sequences were grabbed uncompressed from the device via the DVI port. CT imaging was performed on a 10 slice CT system (Sensation 10, Siemens Healthcare) using a standard clinical protocol (120kV, 250mAs, rotation time 0.5s, acquisition 10×0.75mm, feed/rotation 4.5mm, reconstructed slice width 0.75mm and 5mm). To simulate regular anatomical dimensions and reduce artifacts from extreme hounsfield unit differences at air-tissue/liver-phantom interfaces, the phantom was placed in a water filled basin.

B. *Flow characteristics*



(a) Human arteria carotis



(b) Phantom tube construct

Fig. 4. Measure of velocity with color duplex ultrasound at the human arteria carotis (a) and the tube construct in the model (b) with comparable diameter.

The pulsating pump is able to circulate fluids with up to $0.5\frac{\text{l}}{\text{min}}$. This volume per time is reasonable to supply the tube construct, taking into account that the artificial vessels are designed with $3\text{mm}-4\text{mm}$ in diameter which is a size between the large supporting vessels and the fine ramification of the human liver. We adjusted the valves B_1 and B_2 so that the flow at B_3 was between $0.14\frac{\text{l}}{\text{min}}$ and $0.27\frac{\text{l}}{\text{min}}$. B_3 was closed to an extent so that the upper pressure did not exceed 120mmHg.

Fig. 4(a) presents a measure with color duplex ultrasound (CDxU) at the human carotid artery. This vessel was chosen because its diameter (4mm – 5mm) is similar to the dimension of the model's pipes and it can be scanned at a similar distance as comparable liver vessels during open surgery. The measured speed is in the range of $50\frac{\text{cm}}{\text{sec}}$ to $180\frac{\text{cm}}{\text{sec}}$. The results of measurements in real patients were compared to the experimental values in the model.

The screenshot in Fig. 4(b) represents the typical result of CDxU measures at a pipe section between bifurcation B_1 and B_3 (cp. Fig. 2). Both the diameter (4mm) and the speed ($60\frac{\text{cm}}{\text{sec}} - 150\frac{\text{cm}}{\text{sec}}$) are similar to the values obtained with a comparable human vessel. The variance in the peaks' characteristics between the model (Fig. 4(b)) and the real vessel (Fig. 4(a)) can be ascribed to the pulse shape of the pump, the lack of muscle motion, the BMF additive substance and other restricting simplifications of the model.

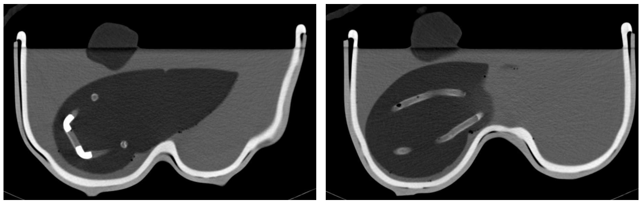
C. Vessel tree in CT and CDU

The aim of the introduced phantom is to represent natural landmarks both in CT and in Doppler US. To prove this feature we depict various views of a CT scan and several US sweeps (cp. Fig. 5) where the vessel tree or a particular bifurcation can be seen and assigned to the tube construct in Fig. 2. Like in real anatomy, only parts of the vessels/tubes are depicted in a single image plane (cp. Fig. 5(a)), therefore we averaged two ranges of slices, one in the front (S_F) from slice 21 to 31 (Fig. 5(b)) and one in the back (S_B) from slice 32 to 46 (Fig. 5(c)). Stack S_F clearly shows the bifurcations B_1 to B_4 whereas stack S_B shows the bifurcations B_5 and B_6. For segmentation, a standard three-dimensional algorithm is proposed as referred to in [1].

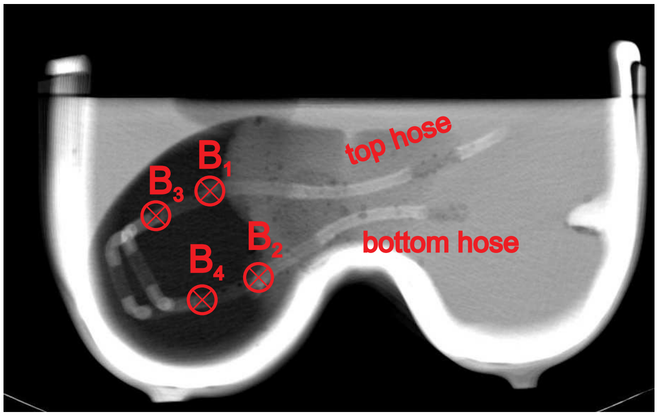
The ALOKA Alpha 7 supports dual view of B-Mode and eFlow, so Fig. 6(a) can visualize the capability of the system to segment the phantom's pipes just by means of the color representation of flow scattering. Besides the bifurcation B_1, we also demonstrate B_3 (6(b)) and B_5 (6(c)). The ALOKA Alpha 7 has a parameter to adjust the time averaging for smoothing the effect of pulsation. Even with lowest parameter value, the eFlow mode turned out to be quite independent of pulsation. This means that in almost every image, some portion of the tube construct was visible and usable for segmenting bifurcations.

IV. CONCLUSION AND FUTURE WORKS

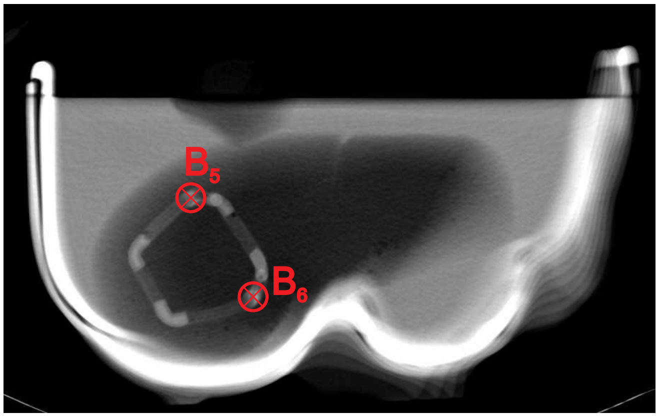
The need for a model with a simulated vessel tree was derived from current literature work. We designed a flow model for applying and evaluating anatomical tree matching and landmark-based elastic registration of color Doppler ultrasound (CDU) volumes with CT data. A tube construct with several bifurcations was integrated in an organ model with realistic look-and-feel. With this model we can simulate blood-mimicking pulsating flow which can be imaged with CDU and CT. Characteristic parameters were shown to be that adjustable to get comparable results to human vessels. Views taken with CDU clearly show pipes and bifurcations with precise borders and thus provide sufficient color information to avoid complex and error prone algorithms for segmentation of vessel trees in grayscale B-Mode images. The possibility of reproducible imaging of a model with CDU while having a corresponding CT available allows for evaluation of algorithms in the field of registration between CT and ultrasound. Future work will be to improve and refine the vessel tree in the organ model. Further more, different rendering and registration algorithms can be applied to the data.



(a) Single slices 27 and 36 of CT scan.

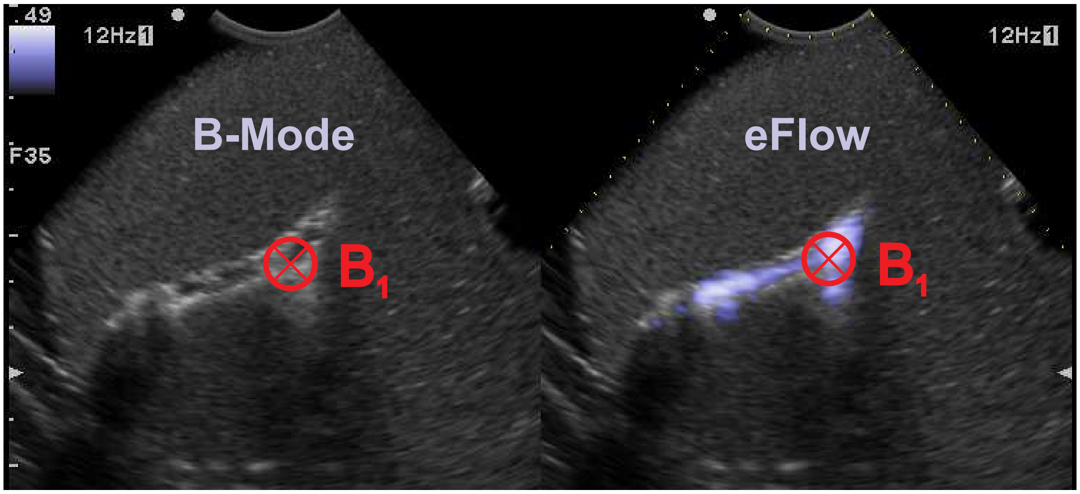


(b) Averaged CT stack S_F (slice 21 to 31).

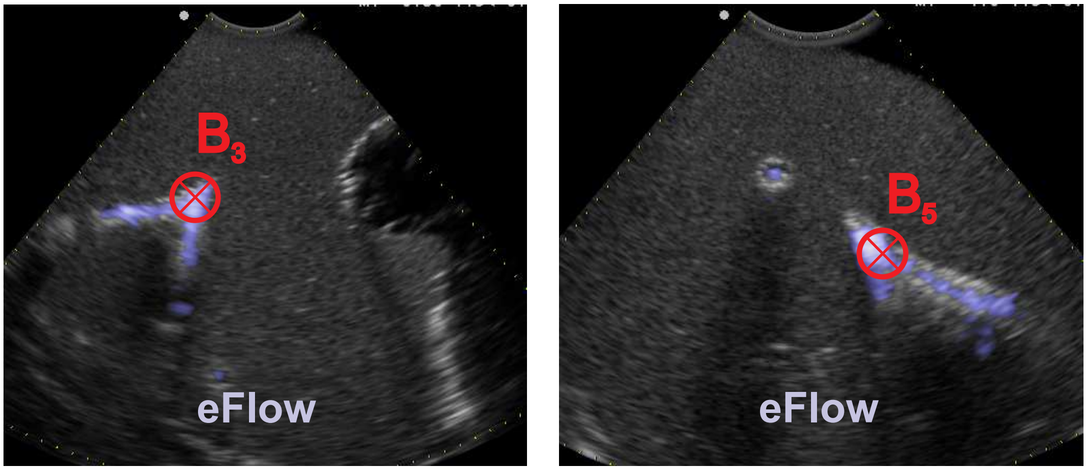


(c) Averaged CT stack S_B (slice 32 to 46).

Fig. 5. Phantom with embedded tube construct imaged with CT. Single slices of CT scan [a] and averaged image stacks [b,c]. Bifurcations are marked with B_1 to B_6.



(a) Dual view of bifurcation B_1 in B-Mode (left) and eFlow (right)



(b) Bifurcation B_3

(c) Bifurcation B_5

Fig. 6. Embedded tube construct imaged with US. Dual view (B-Mode and eFlow) of bifurcation B_1 (a), eFlow view of bifurcation B_3 (b) and bifurcation B_5 (c) in ultrasound snapshots.

V. ACKNOWLEDGMENTS

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