Monitoring of Portal Vein by Three-dimensional Ultrasound Image Tracking and Registration: Toward Hands-free Monitoring of Internal Organs

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Abstract Ultrasound is a convenient non-invasive imaging modality used for the diagnosis or detection of various diseases and assessment of therapeutic effects. However, when imaging internal organs, the ultrasound probe must be handled by an operator. The ability to perform hands-free ultrasound imaging of internal organs is likely to offer an unprecedented advantage in various situations such as internal organ monitoring during exercise tests and prolonged monitoring. Toward this end, we have developed a new method of hands-free monitoring using three-dimensional (3D) ultrasound and used this method in portal vein monitoring, which is important for functional evaluation of hepatic and gastrointestinal systems. In previous studies, we developed a hand-made probe holder and used it to capture images of the portal vein, using image tracking and registration to compare the same position of the portal vein. In this study, we first used an abdomen phantom to assess image tracking qualitatively and quantitatively. After validating the method on the phantom, we monitored the portal vein in three healthy subjects using our 3D ultrasound method. Image tracking and registration of the portal veins in three subjects were successfully performed offline. Finally, respiratory analysis and vein diameter measurement were performed based on the image tracking results. The respiratory analysis quantified the respiration-induced portal vein movements. The vein diameter showed changes that might be induced by respiration and heartbeat. These results indicate that our 3D ultrasound method is a potentially useful tool for hands-free monitoring of internal organs.

Keywords: three-dimensional ultrasound, portal vein, registration, hands-free monitoring.

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1. Introduction
Ultrasound imaging systems are useful for the diagnosis or detection of various diseases, the assessment of treatment effects, and other diagnostic applications. The key advantages of ultrasound are that it is non-invasive and convenient to operate. However, during ultrasound imaging of internal organs, an operator, such as a doctor or a medical technologist, must hold the ultrasound probe, which is a limitation. To be able to perform hands-free ultrasound imaging of internal organs would offer an unprecedented advantage in various situations such as internal organ monitoring during exercise tests and prolonged monitoring.

Chandraratna et al. [1, 2] and Nakashiki et al. [3] attempted hands-free monitoring of cardiac ultrasound images for approximately 10 min during a treadmill test. They first developed an ultrasound transducer that acquired images while being attached to the chest, and used the transducer to monitor cardiac images during a treadmill test. The authors suggested that the ultrasound images can help detect left ventricular motion abnormalities during exercise earlier than when using electrocardiograph. However, their systems have not been used in clinical settings. A possible reason for the lack of popularity is that the organs are captured as two-dimensional (2D) images. 2D imaging cannot continuously capture the same position of the organ. Capturing the same position of a moving organ via robotic control of the ultrasound probe has been attempted in several studies [4, 5]. However, it is not applicable to exercise tests or long-time monitoring.

We considered that 3D organ capture would overcome the shortcomings of 2D imaging. In the first trial, we endeavored to develop a new method for hands-free monitoring using a commercially available 3D ultra-
sound system and a hand-made probe holder [6–9].

In our previous studies, we first applied this method for flow-mediated vasodilatation analysis [6] and then focused on portal vein imaging [7–9]. The portal vein is a blood vessel that supplies blood flow from several digestive organs to the liver. The portal vein branches into left and right immediately before entering the liver (Fig. 1). The portal vein was selected for our study because it can be observed easily using an ultrasound system [10] and is useful for the assessment of hepatic and gastrointestinal functions [11, 12]. For example, hands-free monitoring of the portal vein would allow functional evaluation before and after meals. In a previous study [7], we developed a method for holding the probe and tracking and registering the images of the liver. We then applied this method to a healthy subject. Although we tried to validate our method on an abdomen phantom [8], it was partially inaccurate. We also showed respiratory analysis and diameter measurements [9] as examples of effective utilization of the data from our system. Although these results suggested that a 3D ultrasound system can be used for the hands-free monitoring of the portal vein, some challenges remained, including (1) precise validation of tracking and registration procedures, (2) confirming the feasibility in several subjects or in several trials for separately acquired dataset, and (3) an online or a real-time system.

In the present study, we tried to resolve the above issues (1) and (2). We first validated our method on an abdomen phantom using a more precise method compared with that used in our previous study [8]. We confirmed the good performance of the image tracking and registration procedures, and subsequently applied the method to three healthy subjects including a subject who participated in the previous studies. From the three subjects, two datasets each were obtained from different times, which were used to confirm the feasibility of comparing separately acquired datasets. All six datasets were processed, and image tracking and registration were satisfactorily performed. The results were post-processed for respiratory analysis and diameter measurements.

2. Methods

This study conformed to the ethical principles of the Declaration of Helsinki. Written and informed consent was obtained from each subject. The study was approved by the Medical Ethics Committee of the Kyoto University (No. R0614).

Figure 2 shows the overall system configuration of our system. Details will be explained in the following sections.

2.1 Equipment and software

We used the LOGIQ7 ultrasound system (GE Healthcare, US) with a 4D3C-L probe. This system generates 3D/4D images by mechanical scanning using a convex-type electronic scan transducer. The probe was secured on the abdomen using a hand-made probe holder [6] (Figs. 2 and 3).

The 3D ultrasound system used in this study cannot transfer 3D image data to a computer in real time because the acquired data must first be transferred to the system hard drive. The 3D image reconstruction and image processing were performed offline (Fig. 2) using an algorithm programmed in C language. Image processing was performed using a Mac Pro (Apple, US, CPU 3.7 GHz, Quad-Core Intel Xeon, Memory 64 GB). All reconstructed 3D images had a voxel size of 0.29 × 0.29 × 0.29 mm³.

Figure 4 shows three cross-sectional images and three time sequence images (M-mode images) of the ac-

![Fig. 1 Anatomy of portal vein and liver.](image1)

![Fig. 2 Overall system diagram.](image2)
quired 3D ultrasound images.

2.2 Image tracking and registration

For monitoring of the portal vein, the portal vein must remain at the same position in every volume image. However, the portal vein moves constantly on the ultrasound image as the subject breathes. To decrease the respiratory motion, we tracked and co-registered the position of the portal vein. Image tracking was performed using the 3D template-matching method will be described in the following paragraph. The process was performed offline as shown in Fig. 2, because of the limitation of the ultrasound system employed. Therefore, in our study, real-time or high-speed image processing was not pursued.

Figure 5 shows a diagram of our image tracking and registration method. The method was briefly described in previous reports [7–9]. In our study, we did not aim to develop a full automated method, and some user interactions were required for setting the template volume [Fig. 5(1)]. Firstly, the reference volume was defined as the volume in which the bifurcation and main trunk of the portal vein were clearly observed in the center of FOV. The template volume was then extracted manually from the selected reference volume and included the bifurcation and main trunk of the portal vein. Subsequently, a reference point was defined manually at the center of the bifurcation of the portal vein in the reference volume. Then, image tracking [Fig. 5(2)] and registration [Fig. 5(3)] were performed by a rigid transformation. We used the residual sum of the squares of intensities between each volume and the template volume as the matching measure. As mentioned before, we did not pursue high-speed image processing this time. Therefore, no hardware acceleration was used, and a simple full searching method with two conventional speeding up methods were implemented. One was the sequential similarity detection algorithm (SSDA) [13], the other was the multi-scale approach in searching for the rotation space. In the multi-scale approach, we firstly applied registration for translation only, and then applied registration including rotation in two increments of the last step, and finally applied registration including rotation in fine increments. The rotation center was set as the reference point explained above.
2.3 Evaluation of the tracking accuracy using a phantom

The accuracy of the image tracking method was evaluated on an abdomen phantom (Echozy, Kyoto Kagaku Co., Ltd., Japan). To simulate the respiration-induced movement of the portal vein, we acquired volumes while manually moving the probe. Figure 6 shows directions of probe movements on the phantom. Four types of movement were evaluated, namely, cranio-caudal translation, left-right translation, z-axis rotation, and x-axis rotation. For example, when the probe moves in a cranio-to-caudal direction, the portal vein moves in the direction of the negative x-axis and the z-axis on the ultrasound images. The translation of the image tracking was performed in 1-voxel units (0.29 mm), and the rotation ranged from $-12.5^\circ$ to $12.5^\circ$ in 0.5$^\circ$ increments. A similar experiment performed in our previous study [8] was inaccurate because the portal vein moved out of the field of view (FOV) due to excessive movements of the probe. Therefore, we obtained the present volumes while moving the probe within a suitable range.

Since the probe was moved manually, it was very difficult to measure probe motion accurately. Then, we evaluated the tracking method using the image changing rate (ICR) defined as follows:

$$ICR = \sqrt{\frac{\sum_{x=1}^{X} \sum_{y=1}^{Y} \sum_{z=1}^{Z} \left[ f(a+x, b+y, c+z) - r(x, y, z) \right]^2}{X \times Y \times Z}} \times 100 \%$$

$$r_{max}$$

where

- $f(x, y, z)$ : the intensity of the voxel in each volume,
- $r(x, y, z)$ : the intensity of the voxel in the reference volume,
- $a, b, c$ : the position of the volume of interest in the volume,
- $X, Y, Z$ : the matrix size of the region of interest,
- $r_{max}$ : the maximum intensity of the reference volume.

The ICR was calculated in the volume of interest (VOI) that included the bifurcation and the main trunk of the portal vein.

Then, the ICR between the template and registered volumes was compared with the percentage standard deviation of the intensity relative to the maximum intensity in the liver parenchyma region. Because this region of the phantom is made of a uniform material, the standard deviation of its volume intensity provides an estimate of the noise level in the volume.

2.4 Application in healthy subjects

2.4.1 Healthy human imaging and registration

Three healthy subjects participated in the study (Table 1). All subjects underwent two imaging sessions of approximately 600 s. The 600-s data were acquired by repeating 200-s imaging scan twice at an interval of approximately 200 s. The second set of 600-s data was acquired approximately 1 month after the first set was acquired. The volume rate was approximately 10 volumes/s. Subjects rested in the supine position and breathed freely during the recording. To fix the probe in position, we clamped the probe in a hand-made probe holder (Fig. 3) [7]. The probe was fixed in a position such that in the end-expiration phase, the portal vein main trunk was visualized in the center of FOV. Table 1 also shows the matrix size of each dataset.

Owing to the movement of the portal vein during respiration, image tracking and registration are necessary to compare the volumes. Here, image tracking and co-registration of these volumes were performed offline via the 3D template-matching method explained in section 2.2. The template of each dataset was extracted from the volume in which the portal vein main trunk was visualized in the center of FOV, which was presumably in the end-expiration phase. From preliminary experiments, the range and the increments in rotation estimation were defined as from $-16^\circ$ to $16^\circ$ and $1^\circ$, respectively.

Then, the co-registered second datasets ($A_2$, $B_2$, and $C_2$) were registered again to the first co-registered datasets ($A_1$, $B_1$, and $C_1$), respectively, to confirm the possibility of comparing datasets acquired 1 month apart.

2.4.2 Post-processing

The registered image sequence should provide several pieces of information during subsequent post-processing. In this study, respiratory analysis and vein diameter measurement were performed on all registered datasets.

To analyze the respiratory motion, we measured the 3D displacement of the tracked reference points from the original reference position. The position was defined in the reference volume. The distance between the tracked and original reference points was also calculated from the image tracking results acquired in section 2.4.1.

The diameter of the main trunk of the portal vein was measured by applying the additional 3D tem-
plate-matching method. Two templates, on opposite sides of the main trunk vessel wall, were extracted manually from the reference volume. The tracking was performed perpendicular to the portal vein axis. The distance between the matching points of the two templates was defined as the portal vein diameter. The measured diameter was processed by a median filter and a threshold based on a histogram for the elimination of outliers.

To confirm that these measurements captured the influence of respiration and heartbeats, we performed a Fourier analysis of the diameter change and displacement of the portal vein.

3. Results

3.1 Evaluation of the tracking accuracy using the phantom

Figure 7 shows the result of the image tracking and registration. Figure 8 shows estimated translations and rotations during the image tracking. The translations and rotations corresponded closely to the manual probe movements. In case of rotation around the x- and z-axes, because the axes of rotation were out of the FOV, the portal vein movement also included translation in addition to rotation. In case of rotation around the x-axis, because manual control of the probe was very difficult, the probe movement also included rotation around the z-axis in addition to that around the x-axis. Figure 9 shows the ICR between the first volume and each subsequent volume. The maximum ICR (6.5%) was comparable to the noise level in the liver parenchyma region (6.1%).

3.2 Application in healthy subjects

3.2.1 Healthy human imaging and registration

Visual inspection of the B-mode movies (Supplemental movie) confirmed that the ultrasound system could continuously capture the portal vein for up to 600 s using the hand-made probe holder.

Figure 10 shows the original and co-registered B/M-mode images of datasets A2, B2, and C2. The B-mode images are superimposed images of the red template and green original/co-registered images. As shown in these images, tracking and co-registration were performed well, except for a part of dataset C2. In dataset C2, as can be seen from Fig. 10-C2 (560–580 s), image tracking failed in the expiration phase because the main trunk of the portal vein was greatly deformed. In datasets A1, B1, and C1 also those processes were performed well, except for a part of dataset B1 (Supplemental Fig. 1). In dataset B1, the image tracking could not be performed during the 172–176-s period because a small part of the VOI had moved out of the FOV. By visual inspection of the co-registered B-mode movies (Supplemental movie), two clinicians confirmed that image tracking was performed well, except for the above-mentioned parts of the image.

Table 1 Data of the three healthy subjects.

| Subject | Data  | Matrix Size          |
|---------|-------|----------------------|
| A       | A1    | 334×156×233×3974 (1987+1987) |
| Male, 50’s | A2    | 347×164×218×3950 (1975+1975) |
| B       | B1    | 339×190×270×3948 (1974+1974) |
| Male, 20’s | B2    | 346×201×260×3903 (1952+1951) |
| C       | C1    | 328×198×300×3969 (1985+1984) |
| Male, 20’t | C2   | 338×203×310×3898 (1948+1950) |
datasets B_1 and C_2.

The image patterns are slightly different between the 0–20-s and 560–580-s images in Fig. 10–C_2, which is attributable to the unstable respiratory pattern of subject C during monitoring. In Supplemental Fig. 1, which shows all datasets during all 600-s periods, a difference in motion pattern between datasets C_1 and C_2 is also observed. This indicates weak reproducibility of the respiratory pattern in subject C.

Although registration failed in small parts of datasets B_1 and C_2, image tracking was normalized upon recovery of the portal vein position or shape.

Figure 11 shows superimposed original and co-registered B/M-mode images of datasets B_1 and B_2, when dataset B_2 was co-registered to dataset B_1. Visual observation of the movies confirmed that the co-registration was performed well in datasets of all subjects. Supplemental Fig. 2 shows co-registration results of all datasets.

3.2.2 Post-processing

Figure 12 shows 3D trajectory of the portal vein position in dataset B_2 over a 20-s period from 0 s to 20 s, which includes four typical stable respiratory cycles. The portal vein mainly moved in the caudal direction during the inspiration phase and in the cranial direction during the expiration phase. The position was stable until the next inspiration. In the other datasets, a similar movement tendency was observed. However, a more detailed verification showed some differences between the subjects [14], which are not discussed in this paper.

Figure 13 shows the vein diameter and displacement at the reference point of datasets A_2, B_2, and C_2 during 0–200-s period. Supplemental Fig. 3 shows results of all datasets. Figure 14 shows an enlarged 0–20-s period of dataset B_2, which is the same period as shown in Fig. 12. The diameter exhibited periodic changes. The portal vein movement was unstable during the inspiration and early-expiration phases. Figure 15 shows the result of the Fourier analysis. The blue and red lines show the amplitude spectrum of diameter change and displacement, respectively. The average of the amplitude spectrum during the 0–200-s and 400–600-s periods in dataset B_2 was calculated. Large values near 0.2 and 1.2 Hz appear in the spectrum of the diameter change. In datasets A_1, A_2, and B_1, large values near the same frequencies were also observed (Supplemental Fig. 4).
4. Discussion

4.1 Evaluation of the tracking accuracy using the phantom

The proposed method for image tracking and co-registration between the template and each subsequent volume was performed with errors comparable to the noise level. This is corroborated by the fact that the maximum ICR was almost equal to the noise level (Fig. 9). This finding indicates that the image tracking and co-registration were performed with a sufficient degree of accuracy.

It would be, however, better to evaluate the error of estimated probe motion directly. To this end, the actual probe motion should be measured accurately.

4.2 Application in healthy subjects

4.2.1 Healthy human imaging and registration

This study shows the feasibility of hands-free monitoring of internal organs using a commercially available 3D ultrasound system and a hand-made probe holder. Furthermore, images captured using the hands-free method can be registered.

In this study, all subjects rested in the supine position. We also tested 3D imaging using our hand-made probe holder in both sitting and standing positions for a few minutes. The image quality obtained was comparable to that obtained in the supine position, suggesting that our method can be used in various settings such as during an exercise test.

In almost all images during the 400–600-s period in all datasets, which were acquired 200 s after acquisition of the images for the 0–200-s period, the image tracking and co-registration were performed well, suggesting that intermittent monitoring over a longer time period is possible by repeating the image capture. For example, extension of the monitoring time to approximately 1 h will allow pre- and post-prandial functional evaluation.

The second 600-s set was co-registered to the first set that was acquired 1 month earlier. The result suggests that data from different acquisition time can be compared, which may be useful for the assessment of therapeutic effects.

In our previous study [8], we demonstrated that the 3D ultrasound image of the abdomen phantom was not degraded for 6 h. Therefore, prolonged monitoring would be feasible. Currently, we used the commercially available ultrasound system. However, the availability of smaller probes with faster volume capture is expected in the near future. When these become available, hands-free monitoring will be possible in various situations including monitoring over a longer period of time.

We performed rigid registration in this study, and showed its feasibility in the application to portal vein monitoring. Non-rigid registration would be, however, necessary in general. Inclusion of non-rigid registration is very important to expand our method of hands-free monitoring to various situations.

4.3 Post-processing

Although post-processing of several parameters such as 3D vessel extraction and reconstruction is possible [7], we performed respiratory analysis and vein diameter measurements in this study.

The respiratory analysis quantified the portal vein
movement. We performed image tracking to monitor the portal vein. However, another possible approach is to utilize the respiratory gating method. Because our respiratory analysis quantifies the portal vein movement in 3D, it would be useful in planning an image gating method.

The vein diameter measurements quantitatively captured continuous changes. On Fourier analysis, large values near the 0.2 and 1.2 Hz regions (Fig. 15) appeared to correspond to the respiratory and cardiac cycles, respectively. The inferior vena cava adjacent to the portal vein was found to be pulsating, and was observed to periodically push the portal vein on the axial view B-mode images of the portal vein. The respiratory movement and inferior vena cava pulsations not only displaced the portal vein but also deformed its shape. However, we only applied rigid registration in this study, and it appeared that the diameter measurement process compensated for the small deformations in the portal vein. In the case of greater deformation, non-rigid registration will be necessary.

The region of high value in the amplitude spectrum was similar in the datasets of subjects A and B. Although peaks were observed in the dataset of subject C, they were slightly lower than those observed in other datasets (Supplemental Fig. 4), which may be attributable to the unstable respiration of subject C. More details regarding this phenomenon are discussed elsewhere [14].

4.4 Future study

All data processing procedures in this study were performed offline. However, because real-time processing has proven promising in some studies, we aim to incorporate real-time processing in our monitoring method. Since we did not implement any special speeding up method, our calculation times of template matching were far from real-time processing. The average calculation times without and with rotational estimation were 1.6 and 58.7 s/volume, respectively. However, by including a more efficient registration algorithm and hardware acceleration such as GPU-based method, real-time processing would be feasible. For example, Banerjee et al. [15] achieved 0.12 s/volume for registration of 3D ultrasound volumes that had a similar matrix size of ours.

In addition, owing to limitations of the ultrasound system used in this study, we acquired and processed only B-mode morphological images. An ultrasound system that can acquire 3D Doppler images will allow more detailed study of the portal vein function and improve the utility of hands-free monitoring. Onogi et al. [16] registered morphological and 3D Doppler ultrasound images of artificial blood vessels. Application of real-time processing and 3D Doppler imaging to our method would allow consistent sampling of the Doppler images at the same position. With this method, it is not necessary to register different types of images, as described by Onogi et al.

5. Conclusion

This study showed the feasibility of the use of our 3D ultrasound method for hands-free monitoring of the portal vein. We achieved good results of image tracking and registration during a 600-s period and after an interval of approximately 1 month. Furthermore, our method allowed successful completion of respiratory analysis and diameter measurements as post-processing procedures.

We conclude that our 3D ultrasound method is a potentially useful tool for hands-free monitoring of internal organs such as the portal vein.

Conflict of interest

We have no conflicts of interest with any companies or commercial organizations based on the definition of the Japanese Society for Medical and Biological Engineering.

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References

1. Chandraratna PAN, Vijayasekaran S, Brar P, Tzeng J: ‘Hands-free’ continuous transthoracic monitoring of pericardiocentesis using a novel ultrasound transducer. Echocardiography. 20(6), pp. 491–494, 2003.
2. Chandraratna PAN, Gajanayaka R, Makkena SM, Wijegunaratne K, Hafeez H, Vijayasekaran S, Ali A: ‘Hands-free’ continuous echocardiography during treadmill exercise using a novel ultrasound transducer. Echocardiography. 27(5), pp. 563–566, 2010.
3. Nakashiki K, Kisanuki A, Otsuji Y, Yoshifuku S, Yuasa T, Takasaki K, Kuwahara E, Yu B, Uemura T, Mizukami N, Hamasaki S, Minagoe S, Tei C: Usefulness of a novel ultrasound transducer for continuous monitoring treadmill exercise echocardiography to assess coronary artery disease. Circ J. 70(10), pp. 1297–1302, 2006.
4. Mustafa ASB, Ishii T, Matsunaga Y, Nakadate R, Ishii H, Ogawa K, Saito A, Sugawara M: Human abdomen recognition using camera and force sensor in medical robot system for automatic ultrasound scan. Proc of 35th Annual International Conference of the IEEE EMBS. Osaka, pp. 4855–4858, 2013.
5. Onogi S, Irisawa S, Natsume K, Koda R, Masada K: Position control of ultrasound transducer by parallel link robot for ultrasonic therapy in blood vessel. Adv Biomed Eng. 2, pp. 117–123, 2013.
6. Motoyama K, Ueno T, Ishizu K, Fujii Y, Shina T, Sugimoto N: A 3D ultrasound image tracking of brachial artery for flow-mediated vasodilation analysis. Proc of 34th Symposium on Ultrasonic Electronics. Kyoto, pp. 523–524, 2013.
7. Teratoko T, Ueno T, Ishizu K, Fujii Y, Shina T, Sugimoto N: A
3D ultrasound image registration and extraction of portal vein for long time monitoring. Proc of 35th Symposium on Ultrasonic Electronics. Tokyo, pp. 535–536, 2014.

8. Terada I, Teratoko T, Ueno T, Ishizu K, Fujii Y, Shiina T, Sugimoto N: Evaluation of image quality and registration accuracy of 3D ultrasound portal vein images for long monitoring. IEICE Tech Rep. MI2015-123, pp. 241–246, 2016. (in Japanese).

9. Terada I, Togoe Y, Ueno T, Ishizu K, Fujii Y, Shiina T, Sugimoto N: Long monitoring of portal vein with 3D ultrasound: Image tracking, respiratory motion analysis and diameter measurement. Proc of 37th Symposium on Ultrasonic Electronics. Busan, 2P5–1, 37, 2016.

10. Kato R, Ishida H: Portal vein emphasis on sonographic findings normal image and abnormal image. Jpn J Med Ultrasonics. 36(3), pp. 329–340, 2009. (in Japanese).

11. Taniguchi N, Takano R, Yasuda Y, Wang Y, Nakamura M, Kawa F, Ono M, Yokota K, Omoto K, Itoh K: Estimation of portal venous flow using the color Doppler method and velocity profiles. Jpn J Med Ultrasonics. 23(10), pp. 731–736, 1996. (in Japanese).

12. Nihei Y, Sasanuma H, Yasuda Y: Experimental evaluation of portal venous pulsatile flow synchronized with heartbeat intervals: effects of vascular clamping on portal hemodynamics. Jpn J Med Ultrasonics. 40(1), pp. 9–18, 2013.

13. Onoe M, Maeda N, Saito M: Image Registration by Sequential Similarity Detection Algorithm. J Inf Process Soc Jpn. 17(7), pp. 634–640, 1976. (in Japanese).

14. Terada I, Ueno T, Ishizu K, Fujii Y, Shiina T, Sugimoto N: A preliminary study of portal vein’s 3D respiratory motion analysis with 3D ultrasound. Proc of 38th Symposium on Ultrasonic Electronics. Miyagi, 1J1–2, 38, 2017.

15. Banerjee J, Klink C, Peters ED, Niessen WJ, Moelker A, van Walsum T: Fast and robust 3D ultrasound registration - Block and game theoretic matching. Med Image Anal. 20(1), pp. 173–183, 2015.

16. Onogi S, Phan TH, Mochizuki M, Masuda K: Automatic Doppler volume fusion of 3D ultrasound using point-based registration of shared bifurcation points. Adv Biomed Eng. 4, pp. 27–34, 2015.

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