Cardiac variation of internal jugular vein as a marker of volume change in haemorrhagic shock

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Abstract

Background. Fluid resuscitation is crucial to counter acute haemorrhagic shock and requires prompt and accurate intravascular volume estimation for optimal fluid administration. This study aimed to evaluate whether cardiac variation of the internal jugular vein (IJV), measured by ultrasound, could detect hypovolemic status and predict response to fluid resuscitation.

Methods. Autologous blood transfusion patients for their own elective surgeries were prospectively enrolled at our blood donation centre from August 2014 to January 2015., and movies of vertical B-mode ultrasonography of the IJV were recorded at five points during blood donation, namely, before donation, during donation, end of donation, end of fluid replacement and after hemostasis. Cardiac variation in IJV area and circumference were objectively measured using an automated extraction programme, along with blood pressure and heart rate.

Results. We screened 140patients and data from 104 were eventually evaluated. Among the variables analysed, only collapse index area (CIa) and collapse index circumference (CIc) could detect both intravascular volume loss and response to fluid administration

Conclusions. The cardiac variation of IJV may be a reliable indicator of intravascular volume loss and response to fluid administration in haemorrhagic shock.

Background

Acute haemorrhagic shock can occur in several different clinical settings, such as in the emergency room, the operating room and the intensive care units, and because early treatment ensures a good clinical course, prompt and accurate assessment of intravascular volume status is essential. However, it can be challenging to accurately recognise hypovolemic status based on physical examination, vital sings and laboratory tests, especially during the early stages of haemorrhagic shock[1].

Many invasive and noninvasive procedures have been developed for assessing intravascular volume status[2, 3, 4]. Pulmonary artery catheterisation (PAC) can measure central venous pressure (CVP), pulmonary artery pressure and pulmonary artery occlusion pressure, and is considered the best procedure for volume status assessment, even though associated complications are its disadvantages[5]. Stroke volume variation (SVV) can be measured less invasively than PAC and is now widely used for predicting fluid responsiveness. Many other devices for volume status assessment have been developed; however, disadvantages in terms of invasiveness and requirement of special equipment remain[2]. Ultrasonography is an easy and useful noninvasive medical imaging technique. Respiration-induced variation in inferior vena cava (IVC) diameter is reported to be a marker of hypovolemic shock and a predictor of fluid responsiveness, and both inspiratory and expiratory IVC diameter correlate with CVP[6]. Additionally, respiratory variation of IVC diameter is expected to be a good parameter that guides fluid therapy[7]. However, IVC measurement may be difficult in some cases because of the excessive presence of fatty

tissue or bowel gas. In contrast, the IJV can be observed more easily than the IVC, and respiratory variation in IJV is also reported to be useful for the assessment to intravascular volume status[8].

Blood donation can be used as a model of haemorrhagic shock as it rapidly decreases intravascular volume; however, it is known that vital sings during the procedure show only mild changes, and WHO guidelines for blood donor selection have addressed this issue to prevent complications[9]. Further, respiratory variation of IVC and IJV characteristics have been studied as potential markers of intravascular volume status assessment during blood donation because a decrease in IVC diameter during inspiration and expiration, a change in indirect CVP measurement based on the IJV and significant difference in respiratory variation of IJV, have all been observed after blood donation[10, 11, 12]. However, these studies suffer from certain problems such as inter-rater reliability and objectivity, and the long recording time required for establishing respiratory variation[13, 14].

We have previously evaluated cardiac variation of the vena cava, which refers to venous vibration that occurs due to changes in cardiac rhythm. This method has the advantage of requiring a shorter recording time than respiratory variation. Therefore, we have developed an automatic image tracking system to analyse changes in IJV, which would be free from inter-rater reliability and objectivity. Previously, we have shown that cardiac variations of IVC and IJV were equally useful for detecting acute intravascular volume change; however, these studies evaluated variation only during dehydration and did not evaluate responsiveness to fluid resuscitation. Additionally, the sample size in these studies was small[15, 16, 17]. Therefore, we investigated the usefulness of cardiac variation in IJV, not only for detecting reduced intravascular volume but also for predicting the response to fluid resuscitation in autologous blood transfusion patients, who adequately mimicked acute haemorrhage that required immediate fluid replacement.

Methods

Patients

This prospective study was conducted from August 2014 to January 2015 at the blood donation centre of The University of Tokyo Hospital. This study was approved by the ethical committee of The University of Tokyo Hospital. Written informed consent was obtained from every participant and all individuals who were autologous blood donors for their own elective surgeries were included in this study. Exclusion criteria were pregnancy, arrhythmia, congenital cardiac anomalies and history of radiotherapy or neck surgery. Individuals with insufficient data were also excluded.

The volume of blood donated was decided based on haemoglobin levels, body weight and height of the individual and all donors were administered 500 ml crystalloid (in 30 minutes) after donation.

Measurements

The patients were asked to rest in a supine position for few minutes and ultrasonography videos were recorded at 5 points, namely, before donation (T0), halfway during donation (T1), end of donation (T2), during fluid replacement (T3) and after hemostasis (T4). T1 was determined using the real-time volume metre at approximately 200 mL which represented half the total volume of donation. The ultrasound probe was placed on the skin at a distance of one finger breadth above the right clavicular fossa and was vertically aligned. The IJV was visualised on short-axis views of the horizontal sections in B-mode[16] and the recording time was 4 seconds during the expiratory phase. Ultrasonography was performed using the SonoSite M-Turbo Ultrasound device (FUJIFILM Sono Site Inc, Tokyo, Japan) and a linear probe (HFL38x/13-6MHz). Imaging was performed by two physicians in the transfusion department and heart rate (HR) and blood pressure (BP) were recorded at all the time points.

Blood vessel boundary images were analysed automatically by the extraction module of the modified software developed at the Graduate School of Engineering, University of Tokyo[18]. The algorithm of the programme is based on snake and speckle tracking models, which is an active contour method that can track objects from the previous image. The area and circumference of the IJV were analysed (Fig 1) and the following parameters were calculated:

1. IJVa Max and IJVa Min: the mean of maximum and minimum IJV area in each cardiac cycle during the expiration phase.
2. IJVc Max and IJVc Min: the mean of maximum and minimum IJV circumference in each cardiac cycle during the expiration phase.
3. Collapse index area (CIa): The mean of (maximum –minimum)/(maximum) of area in each cardiac cycle.
4. Collapse index circumference (CIc): The mean of (maximum –minimum)/(maximum) of circumference in each cardiac cycle.

Statistical analysis

Data are shown as mean ± standard deviation or median (interquartile range[IQR]). Statistical analyses were performed using the JMP software (JMP Pro14; SAS Institute Inc, Cary, NC), and 95% confidence interval (CI) for each index was calculated. The values at different time points were evaluated using the Wilcoxon rank-sum test and multiple comparisons were adjusted using the Bonferroni method. The correlation of parameters was evaluated using the Spearman correlation test.

Results

We screened 140 patients for potential enrollment but 36 were excluded because of incomplete data or low ultrasound data quality. Finally, data from 104 patients was analysed in this study. The characteristics of the patients at just before blood donation are summarised in Table 1.

Table 1
Patient characteristics at the beginning of blood donation

age (yr)	**50.2 ± 16.6**
female/male	84/20
height (cm)	159 ± 9
weight (kg)	56.5 ± 11.3
BMI (kg/m^2)	22.3 ± 4.2
Hb (g/dl)	13.3 ± 1.4
donation time (min)	10 ± 6
donation volume (ml)	389 ± 24
HR (/min)	77.1 ± 11.9
MAP (mmHg)	87.1 ± 12.0
BMI, body mass index; Hb, haemoglobin; HR, heart rate; MAP, mean arterial pressure	

Data on parameters such as HR, BP, pulse pressure (PP) and the IJV related values for the 5 time points during blood donation are shown in Table 2. These parameters showed similar results in that they changed only in response to blood loss but not after fluid administration. Changes in IJV parameters due to cardiac variation are shown in Table 2 and all parameters showed similar patterns of temporal changes in response to not only blood loss but also to fluid administration. Although no statistically significant difference was observed in the parameters listed in Table 3, CIa and CIc were significantly different even though temporal changes were identical (Table 2). It should be noted that relative change in CIa and CIc in each patient was larger than that of HR, MAP (mean arterial pressure), and PP (Table 3), suggesting relative change of CIa and CIc might be sensitive parameter in volume change than HR, MAP and PP.

Table 2

Changes in clinical parameters, cardiac variation parameters and cardiac variation collapse index of the internal jugular vein during various stages of blood donation

	T0 before donation	T1 half donation	T2 all donation	T3 fluid replacement	T4 after hemostasis
HR (/min)	71 (64–80)	67 (62–76) *	68 (62–76) *	67 (60–73) *	66 (60–76) *
MAP (mmHg)	86 (79–93)	81 (75–88) *	80 (73–87) *	79 (71–88) *	80 (73–88) *
PP (mmHg)	52 (43–63)	46 (38–56) *	44 (37–54) *	48 (41–56)	49 (39–57)
Cla (%)	15.6 (9.7–21.5)	18.9 (12.5–32.5) *#	21.0 (11.4–35.0) #	14.7 (14.7–22.5)	17.0 (10.0–29.7)
Clc (%)	7.2 (4.6–10.1)	9.3 (5.5–14.9) *#	9.5 (5.6–15.0) *#	6.8 (4.6–9.5)	7.9 (5.0–12.3)
IJVa Max (cm^2)	0.92 (0.6–1.42)	0.67 (0.41–1.06)	0.55 (0.32–0.86)	1.15 (0.80–1.49)	0.95 (0.56–1.42)
IJVa Min (cm^2)	0.77 (0.46–1.22)	0.54 (0.27–0.88)	0.43 (0.20–0.73)	0.96 (0.63–1.36)	0.80 (0.40–1.18)
IJVa Mean (cm^2)	0.85 (0.52–1.34)	0.60 (0.34–0.97)	0.48 (0.27–0.76)	1.06 (0.73–1.45)	0.89 (0.48–1.31)
IJVc Max (cm)	4.25 (3.63–5.02)	3.70 (3.07–4.65)	3.51 (2.68–4.29)	4.57 (3.93–5.22)	4.28 (3.43–5.05)
IJVc Min (cm)	3.94 (3.12–4.69)	3.35 (2.58–4.25)	3.11 (2.25–3.85)	4.26 (3.58–5.05)	3.98 (3.00–4.85)
IJVc Mean (cm)	4.13 (3.28–4.86)	3.53 (2.84–4.45)	3.33 (2.51–4.06)	4.44 (3.75–5.13)	4.09 (3.25–4.96)

*, $p < 0.001$ vs T0 after Bonferroni correction, #, $p < 0.001$ vs T3 after Bonferroni correction

HR, heart rate; MAP, mean arterial pressure; PP, pulse pressure; IJVa, internal jugular vein area; IJVc, internal jugular vein circumference; Cla, collapse index area; Clc, collapse index circumference

Table 3

Relative changes compared to before donation (T0)

	T1 half donation	T2 all donation	T3 fluid replacement	T4 after hemostasis
Cla (%)	1.27 (0.87–1.81)	1.26 (0.88–2.19)	0.89 (0.67–1.22)	1.09 (0.70–1.65)
Clc (%)	1.24 (0.89–1.80)	1.36 (0.76–2.14)	0.89 (0.71–1.22)	1.10 (0.68–1.60)
HR (/min)	0.94 (0.90–1.00)	1.06 (1.00–1.11)	0.93 (0.88–1.01)	0.93 (0.88–0.99)
MAP (mmHg)	0.94 (0.90–1.00)	0.93 (0.89–0.97)	0.93 (0.87–0.98)	0.93 (0.87–0.99)
PP (mmHg)	0.88 (0.77–1.04)	0.87 (0.73–1.02)	0.93 (0.79–1.09)	0.93 (0.80–1.07)

Cla, collapse index area; Clc, collapse index circumference; HR, heart rate; MAP, mean arterial pressure; PP, pulse pressure

The Cla and Clc at T2 (after donation) showed modest but significant correlation with age and BMI (Table 4). Therefore, Cla and Clc were stratified according to BMI (BMI ≧ 25, 25 > BMI ≧ 18.5 and 18.5 > BMI) and age (age ≧ 65 and 65 > age) and reanalysed. Statistical significance in the temporal changes seen above in Cla and Clc were present only in the 25 > BMI ≧ 18.5 and the 65 > age groups (Table 5). This suggested younger patients with normal BMI might show more sensitive response in IJV.

Table 4

Correlation among cardiac variation parameters

	Cla		Clc	
	r	p value	r	p value
age (yr)	−0.48	< 0.0001	−0.49	< 0.0001
BMI (kg/m^2)	−0.32	0.0006	−0.30	0.0022
Hb (g/dl)	0.12	0.2259	0.05	0.6304
donation time (min)	0.10	0.2987	0.11	0.2731
donation volume (ml)	−0.04	0.6517	−0.01	0.9289

Cla, collapse index area; Clc, collapse index circumference; BMI, body mass index; Hb, haemoglobin

Table 5

Subgroup analysis of cardiac variation parameters

CIa (%)	**T0 before donation**	**T1 half donation**	**T2 all donation**	**T3 fluid replacement**	**T4 after hemostasis**
BMI ≧ 25 (n = 23)	15.0 (6.4–27.6)	7.9 (6.0–17.5)	13.0 (7.2–21.9)	9.3 (4.9–22.4)	12.4 (6.3–27.1)
25 > BMI ≧ 18.5 (n = 64)	15.6 (10.5–20.9)	22.0 (14.0–33.0)*#	23.8 (11.8–36.2)*#	14.8 (8.8–22.6)	15.7 (10.6–28.2)
18.5 > BMI (n = 17)	18.4 (12.1–31.8)	26.2 (13.9–35.4)	23.2 (18.6–48.4)	15.2 (10.6–22.6)	21.6 (17.9–31.6)
age ≧ 65 (n = 27)	10.8 (6.5–20.4)	8.3 (5.8–21.5)	9.5 (6.9–18.1)	9.2 (5.4–21.4)	8.0 (5.9–19.9)
65 > age (n = 77)	16.7 (11.2–23.7)	22.7 (15.3–35.9)#	26.3 (16.3–37.7)*#	15.7 (10.1–22.7)	19.9 (12.5–31.0)
CIc (%)	T0 before donation	T1 half donation	T2 all donation	T3 fluid replacement	T4 after hemostasis
BMI ≧ 25 (n = 23)	6.6 (3.6–10.5)	6.6 (3.1–8.1)	5.5 (3.6–11.5)	4.8 (3.0–8.8)	6.4 (2.8–11.3)
25 > BMI ≧ 18.5 (n = 64)	7.2 (4.9–10.0)	10.4 (6.6–15.6)*#	11.2 (6.4–16.9)*#	6.9 (4.8–9.7)	7.6 (5.0–13.3)
18.5 > BMI (n = 17)	7.9 (4.6–12.2)	11.5 (8.0–16.5)	11.5 (7.8–22.3)	7.3 (5.9–10.4)	10.8 (7.6–13.4)
age ≧ 65 (n = 27)	4.6 (3.1–9.9)	4.4 (3.1–8.6)	4.7 (2.7–8.2)	4.8 (2.8–8.8)	5.2 (2.5–7.7)
65 > age (n = 77)	8.1 (5.4–10.5)	11.0 (7.4–16.3)*#	12.0 (7.8–18.9)*#	7.3 (4.9–10.5)	8.9 (5.9–14.1)

*, $p < 0.001$ vs T0 after Bonferroni correction, #, $p < 0.001$ vs T3 after Bonferroni correction

Discussion

Cardiac variation of IJV has not yet been widely evaluated and our results indicate that it is as useful as respiratory variation of IJV in evaluating intravascular volume status. This study demonstrates for the first time that cardiac variation of IJV, measured using an automatic tracing programme, can detect not only intravascular volume loss but also response to fluid administration. Using a clinical model of blood donation by preoperative stable patients is another unique point of this study, because this situation mimics class haemorrhagic shock that was promptly treated by fluid resuscitation.

Significant changes were observed in cardiac variation of IJV during blood donation and subsequent fluid resuscitation (Table 2), while clinical parameters such as BP and HR could not detect changes in volume status, especially during fluid administration (Table 2), indicating the superiority of cardiac variation indices of IJV over regular vital signs.

Among the cardiac variation parameters evaluated, collapse indices CIa and CIc could better predict change of intravascular volume compared to absolute values of area and circumference, suggesting that interindividual anatomical differences in IJV need to be considered. Additionally, our data show a temporal trend rather than single timepoint change, and this is expected to be better than CVP monitoring described previously [19, 20,] because the relative temporal changes in CIa and CIc were more sensitive than clinically used parameters such as BP and HR (Table 3).

Several previous studies have investigated the utility of IJV diameter measurement by ultrasonography for intravascular volume assessment during blood donation[11, 12]. The reported variation in IVJ area during inspiration and expiration was 47 ± 18% before donation and 73 ± 18% after donation[11]. Another study has reported on indirect CVP, defined as vertical height of IJV from the point of complete collapse to the sternal angle of Louis detected by ultrasonography plus 5 cm, to be 6.67 cm (95%CI 6.72–7.07) before donation and 5.98 cm (95%CI 6.09–6.40) after donation[12]. These studies indicate that respiratory variation of IJV might be a reliable indicator of intravascular volume loss.

Previously, we have shown an increase in the collapse index of IVC during dehydration using a passive leg raising test and medical anti-shock trousers[15]. Further, we found a correlation between collapse index of IJV and indirect CVP after dehydration using a sauna[16]; however, these preliminary studies had small sample sizes. Here we show that the collapse index of IJV could be used to monitor dynamic changes in volume status induced by blood loss (200 ~ 400 ml blood donation) and fluid administration (500 ml crystalloid), which are clinically more relevant than those observed in our previous studies. Further, the sample size in this study was much larger (n = 104), but further investigation is necessary to verify these observations in clinically relevant situations such as haemorrhagic trauma and septic shock.

The image tracking software used enabled the analysis of the collapse index because its variation was small over a short period of time. The advantages of the software developed by us for IJV images are objective assessment and automatic analysis. In contrast, in previous studies, respiratory variation analysis was almost always done by a physician, which may be subject to many biases in each physician's skill set[13,14]. The extraction programme for blood vessel boundary identification from ultrasound data used in this study was based on snake and speckle tracking models, which is an active contour method that can trace objects in the previous image[18]. Importantly, the software can be manually adjusted to mark the exact boundary, if there were inter-rater disagreement in measurement. Software use allows better objective assessment than physician measurements, and the development of software with respect to analysis speed and tracking ability will help improve volume status assessment in the clinical settings. Recently, a wearable ultrasound patch monitor that can continuously measure BP change has been developed, and our results indicate a potential for continuous monitoring of cardiac variation of IVJ

for intravascular volume evaluation. Future devices that can measure cardiac variation of IVJ continuously will further develop 0volume evaluation technology in the future[21].

This study has several limitations. First, a comparison of cardiac variation with respiratory variation was not conducted, and many previous studies have reported on the performance of respiratory variation for evaluating intravascular volume loss and fluid challenge response[22,23]. Other clinically available indicators such as CVP, SVV and CRT need to be compared with cardiac variation of IVJ[16, 25]. Second, we cannot exclude the possibility that the patients' sympathetic nerve activation might have affected the obtained results. Although the enrolled patients took rest before blood donation, HR decreased just after donation was started, which may be because of relief from psychological stress. Third, age and BMI affected CIa and CIc; therefore, CIa and CIc may not be able to correctly predict fluid status in high and/or low BMI, and older age patients. It is necessary to analyse BMI and age stratified data in a larger cohort.

Conclusion

The cardiac variation of IJV can be a reliable indicator of intravascular volume loss and response to fluid administration. We employed an automatic tracking programme as it has the advantage of being noninvasive, sensitive and also because it is capable of objective measurement, compared to other clinically used parameters.

Abbreviations

IVJ: internal jugular vein; CIa: collapse index area; CIc: collapse index circumference; PAC: pulmonary artery catheterisation; CVP: central venous pressure; SVV: stroke volume variation; IVC: inferior vena cava; HR: heart rate; BP: blood pressure; PP: pulse pressure; MAP: mean arterial pressure; IQR: interquartile range; CI: confidence interval

Declarations

Ethics approval and consent to participate

This prospective study was approved by the ethical committee of The university of Tokyo Hospital.

Consent for publication

N/A

Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

KT, KN, RI, KD conceived and designed the study. KN, RI and KD contributed to data analysis and interpretation of the data and preparation of the manuscript. RY, TI and HO contributed to the recruitment of participants. TY, EK and IS developed the software automatically extracting blood vessel boundary images. KT wrote the first draft of the manuscript. KN, RI, KD and NM critically reviewed and revised the manuscript for important intellectual content. All authors approved the final version for publication.

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Figures

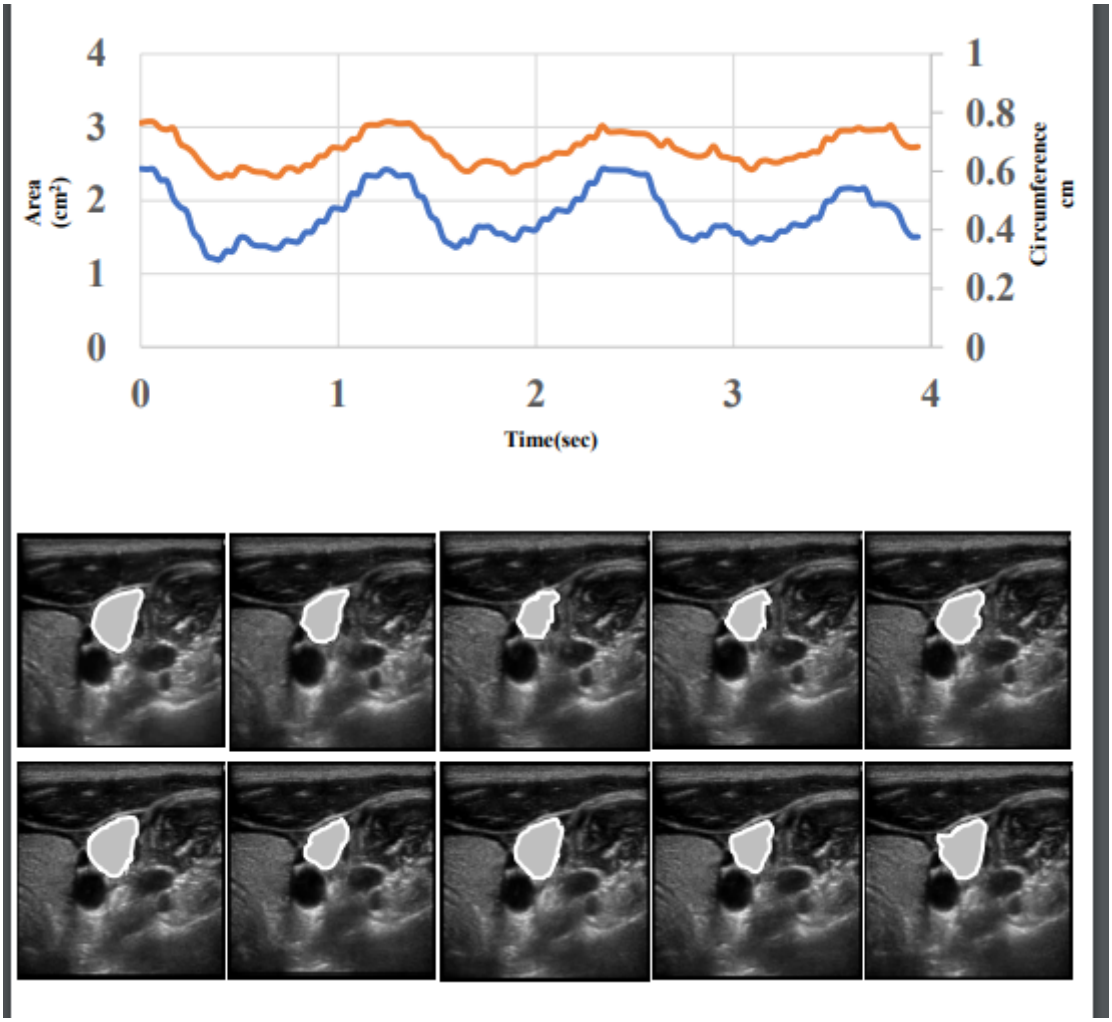

Figure 1

Blood vessel boundary image sampling and automatic tracing The blood vessel boundary images were analysed automatically by the extraction programme based on snake and speckle tracking models. The area (orange line) and circumference (blue line) of the IJV were analysed.