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Effects of respirophasic displacements of inferior vena cava on size measurements from two dimensional ultrasound imaging

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Abstract

Objective. The assessment of the volume status of a patient by ultrasound (US) imaging of inferior vena cava (IVC) is important for diagnosis and prognosis of different clinical conditions. To improve the clinical investigation of IVC, mainly based on unidirectional US (in M-mode), automated processing of two-dimensional US scans (in B-mode) allowed the possibility to track the tissue movements on the visualized plane and to average across different directions. However, the geometry of the IVC outside the visualised plane is not under control and could result in errors that have never been evaluated.

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Methods. We use a method, which integrates information from long and short axis views of IVC (simultaneously acquired in X-plane), to assess the problems in the estimation of IVC diameter by 2D US scans from 8 healthy subjects. Results. The relative movements between US probe and IVC induced the following problems when assessing the IVC diameter by 2D views: median error (i.e., absolute difference with respect to diameter measured in X-plane) of 17% using 2D US scans in long axis view of IVC affected by medio-lateral displacements (median of 4 mm); 7% and 9% of median error when measuring the IVC diameter from a short axis view in the presence of pitch angle (median of 0.12 radians) and cranio-caudal movement (median of 15 mm), respectively. Conclusion. Relative movements of IVC which are out of view of B-mode scans cannot be detected and cause problems in the estimation of IVC diameter.

Keywords: Inferior vena cava, Ultrasound, Tracking

1 **Introduction**

2 Ultrasound (US) scanning is an important medical imaging method due to
3 its non-invasiveness and cost-effectiveness [1][2]. In recent years, this imaging
4 technique has gained remarkable importance in medical structures due to
5 the increased performance of the machines, e.g., in terms of spatial [3] and
6 temporal resolution [4]. X-plane (or biplane) recording allows physicians to
7 simultaneously acquire images of the same tissue in two perpendicular planes,
8 enabling accurate analysis of complex structures [5].

9 Veins are blood vessels that return blood to the heart. They have a low
10 internal pressure and are characterized by a prominent ability to dilate (i.e.,
11 they have a great compliance) and may thus accommodate and eventually
12 redistribute large volumes of fluid [6]. Both arteries and veins have three
13 layers, but arteries have a thicker middle layer to cope with higher blood
14 pressure. Veins are thinner and less stiff, so they are more likely to change
15 shape due to variations of the transmural pressure.

16 The inferior vena cava (IVC), the biggest vein vessel in the human body,
17 is linked directly to the right atrium. The diameter variations of IVC show
18 important information about the volume status of the subject and the central
19 venous pressure [7];[8]. Specifically, the caval index (CI) is commonly used
20 to assess IVC collapsibility, which correlates with the volume status [9] and
21 the right atrial pressure [10]. It is obtained by measuring the maximum and
22 minimum diameters of IVC [11]. However, the assessment of IVC size (and
23 hence also the evaluation of CI) is not standardized [12], so that the measured
24 values could be subject to errors [13]. As a consequence, poor accuracy is
25 achieved when IVC indexes are used to estimate volume responsiveness [14]

26 and right atrial pressure [15]. Some causes of error are related to the following
27 factors.

- 28 1. The use of an M-mode visualization, which selects a fixed US line,
29 making the method prone to respirophasic IVC movements [16, 17].
- 30 2. The different modalities of respiration of the patients [18].
- 31 3. The experience of the operator [13].
- 32 4. The complicated geometry of the IVC and varying collapsibility in dif-
33 ferent directions along its longitudinal axis [19] and cross-section [20].
- 34 5. The three dimensional (3D) movement of the IVC relative to the US
35 probe orientation, including both cranio-caudal and medio-lateral dis-
36 placements [11], together with rotations in different planes [21].

37 Several algorithms have been developed for IVC segmentation to address
38 some of these challenges. These algorithms analyse a single IVC view in B-
39 mode, either longitudinal or transversal to the blood vessel [17, 22, 23]. The
40 visualization in X-plane allows the identification of movements of IVC in the
41 longitudinal and transverse directions at the same time [21]. An algorithm
42 that integrates information from longitudinal and transverse views of the IVC
43 to compensate for motion that adversely affects measurements from a single
44 B-mode scan is described in [21]. In the simulated videos, this algorithm
45 showed impressive performance in mean diameter estimation (with maximum
46 error of 2% relative to the simulated ground truth), correctly compensating
47 for the artefacts caused by the relative movements between IVC and probe.

48 Here, we document the error in the estimation of IVC size when using US
49 scans from a single view in the presence of specific IVC movements, using as
50 reference the algorithm compensating for them [21].

51 Specifically, we focus on the following important IVC displacements: medio-
52 lateral translations, rotation in the longitudinal plane (measured by the pitch
53 angle) and longitudinal translations. Notice that the reference algorithm,
54 integrating long and short axis views of the IVC, was tested on simulated
55 videos in which there was a single vein movement at a time [21]. In real
56 US acquisitions, the three movements can be overlaid and concurrent with a
57 change in vein size. Therefore, predicting the effect of each individual factor
58 in an experimental setting is not trivial.

59 Thus, the aim of this paper is to analyse real data and assess the effects
60 of specific IVC movements on the estimation of its size using US scans from
61 individual B-planes. In fact, there are IVC movements that cannot be ap-
62 preciated on the single 2D view. However, simultaneously monitoring the
63 IVC position and movements on a second 2D plane perpendicular to the first
64 one allows to detect and correct (in part) the possible errors in diameter as-
65 sessment from single 2D views. Thus, the error in IVC size monitoring from
66 single 2D views (related to IVC movements which are visible only out of the
67 plane of view) is quantified using as reference the new algorithm [21], which
68 integrates information from long and short axis views, acquired by X-plane
69 scans.

70 **Materials and Methods**

71 We enrolled 8 healthy subjects. The Ethics Committee of Mauriziano
72 Hospital (Turin) approved the study (approval number 388/2020; experimen-
73 tal protocol identifier v.1, June 1st 2020), and informed consent was obtained
74 according to the policies of the institutional review board. Anonymization

75 was applied to protect patient data. For each patient, an X-plane US video,
76 which provides two simultaneous views of the same target in perpendicular
77 US planes, was acquired using GE Vivid E95 (GE Healthcare, Vingmed
78 Ultrasound, Horten, Norway). The output of the segmentation algorithms
79 in long [19] and short axis [20] was provided as input to our 3D estimation
80 algorithm (implemented in Matlab, the Mathworks, Natick, Massachusetts,
81 USA) to extract IVC size from the combination of the two views [21].

82 *Analysis of data and management of outliers*

83 Diameters were estimated for each frame of the acquired US videoclips,
84 using either of the following 3 methods.

- 85 1. Long-axis views: average of estimations along the IVC course in direc-
86 tion orthogonal to the axis, as in [19].
- 87 2. Short axis view: equivalent diameter estimated from the cross-sectional
88 area of the IVC, as in [20].
- 89 3. X-plane: method proposed in [21], that integrates the information from
90 long and short axis views.

91 Then, the differences between the estimations obtained from the 2D views
92 (either in long or short axis) and those given integrating them (using the X-
93 plane) were investigated as a function of different movements of the IVC with
94 respect to the probe: transverse translation, pitch angle and longitudinal
95 displacement.

96 Some diameter estimations, when displayed in relation to specific IVC
97 movements, showed a large deviation from the main trend. This could be

98 due either to noisy frames determining mistakes in the processing or to pe-
99 culiar relative locations of the probe with respect to the IVC, e.g., a great
100 influence of the other geometrical parameters or an out-of-plane rotation. In
101 fact, different tissue movements (translations, rotations, etc.) and deforma-
102 tions (collapsibility) occur together in experimental data. These particular
103 diameter estimations were considered outliers and removed, as they could
104 affect the interpretation of the effect of the specific geometrical parameter
105 of interest. We identified the outliers by the isolation forest algorithm [24]:
106 binary trees were used to isolate the data and those requiring fewer splits
107 were given higher anomaly scores; outliers were identified as the 10% of data
108 with largest anomaly scores.

109 *Tests*

110 The effect of three possible IVC movements, measured individually and
111 correlated with diameter estimation error, have been investigated.

- 112 1. Medio-lateral translations. The movements of the IVC are easily visible
113 in the transverse section, but they are not noticeable in the long axis
114 view, where they induce an underestimation bias in the size which is
115 more important as the section is further from the centre of the vein.
- 116 2. Variation of the value of the pitch angle. It can be compensated in
117 the longitudinal section by IVC tracking. On the other hand, it is not
118 visible in the short axis view and it has the effect of overestimating
119 the transverse diameter (with a larger effect when the section is further
120 from being orthogonal to the IVC axis).
- 121 3. Longitudinal translations. They are noticeable in the longitudinal sec-
122 tion, where they can be compensated by IVC tracking. An error in

123 diameter estimation is found in the transverse view, if the size of the
124 vein changes along its longitudinal course.

125 Using as reference the diameter estimated by integrating information from
126 the long and short axis views (referred to as 'equivalent 3D diameter'), the
127 percentage errors when using the 2D measurements (i.e., in long or short axis
128 view) were computed as

$$error_{long} = 100 \times \frac{equivalent\ diameter_{long} - equivalent\ 3D\ diameter}{equivalent\ 3D\ diameter} \quad (1)$$

$$error_{transv} = 100 \times \frac{equivalent\ diameter_{transv} - equivalent\ 3D\ diameter}{equivalent\ 3D\ diameter} \quad (2)$$

130 where $equivalent\ diameter_{long}$ and $equivalent\ diameter_{transv}$ are the mea-
131 surements obtained by averaging the diameters estimated in the long axis
132 view (in different locations along the IVC course, in direction orthogonal to
133 the axis, as in [19]) and in the short axis view (obtained from the cross-section
134 area, as in [20]), respectively.

135 *Analysis of the results*

136 The percentage errors of the 2D versus 3D equivalent diameters (esti-
137 mated for each frame of the US scans) were displayed in scatter plots, show-
138 ing their relation with the three investigated IVC movements. Data (after
139 excluding outliers) were interpolated with a line, indicating the standard
140 error (SE).

141 Moreover, the ranges of observed movements and maximal percentage
142 errors were investigated.

143 Given the equivalent diameter obtained by either of the 3 methods, the
144 caval index (CI), the respiratory CI (RCI) and the cardiac CI (CCI) have been

145 computed (as in the previous work [13]). For each time series of equivalent
146 diameter, more indexes have been estimated (i.e., CI and RCI were estimated
147 for each respiratory cycle, CCI was computed for each heartbeat). Then
148 they were averaged, obtaining single values (for all time series of equivalent
149 diameter) which were compared.

150 Finally, the mean diameters and collapsibility indexes were explored and
151 their possible differences among estimation methods (i.e., 2D long and short
152 views or X-plane) were investigated by the Wilcoxon signed rank test for
153 paired comparisons.

154 **Results**

155 We studied the contribution of three geometrical factors to the errors in
156 IVC diameter estimation using longitudinal and transverse views. Each of
157 these factors is here examined in detail, showing first specific examples (in
158 Figures 1-3) and then the overall results (in the following figures).

159 Figure 1 shows a subject characterized by prominent medio-lateral move-
160 ments of the IVC and for whom the diameters estimated by different methods
161 differ significantly. Two frames are selected for which the displacement of
162 the longitudinal plane from the IVC centre was either the smallest or the
163 largest. At the bottom of the figure, the three estimated diameters are dis-
164 placed over time. The corresponding time of the two frames reported above
165 has been highlighted. The difference between the diameters estimated from
166 the long axis, short axis and X-plane views was minimal when the centre of
167 the IVC was close to the tilt line indicating the long axis section, but it was
168 significant at maximum translation. The equivalent 3D diameter is estimated

169 compensating for the medio-lateral translation by using the short axis view.
170 Thus, we can assume that it is not affected by the medio-lateral translation,
171 contrary to the longitudinal diameter, which behaves very differently from
172 the estimation from the cross-section when the displacement is large.

173 The effect of the estimated IVC rotation in the long axis plane (i.e., the
174 pitch) on diameter measurement is shown in Figure 2. Again, two frames were
175 selected to show different conditions: the first where the longitudinal axis of
176 IVC shows some pitch angle with the tilt line indicating the direction of the
177 short axis section and the second in which they are almost perpendicular.
178 Due to the pitch angle visible in the longitudinal view, the cross-section is
179 larger than when it is taken orthogonal to the IVC axis, so that the equivalent
180 diameter estimated from the short axis view has a positive bias, as shown in
181 the traces reported in the lower part of the Figure. The equivalent diameter
182 obtained processing the two sections from the X-plane view compensates the
183 effect of this error. Notice that, when the transverse section is orthogonal to
184 the IVC axis (i.e., for the second frame), the three estimated diameters are
185 almost identical.

186 The third case, i.e., longitudinal translation, is shown in Figure 3. An IVC
187 with a conical shape, as for the subject chosen for this figure, emphasizes the
188 effect of this cranio-caudal translation. Two frames were chosen in which the
189 relative translation of the cross-section is quite large. The three estimations
190 of the diameter (by 2D views in B-mode in long and short axis and X-plane)
191 were almost identical for the first frame, but the translation largely affected
192 the cross-section for the second frame.

193 From the specific examples in Figures 1-3, notice a common interesting

194 thread (that we'll find again later, in Figure 8, where the entire dataset is
195 considered): the long axis view provides in general smaller estimates than the
196 short axis, as the first can be biased negatively by a medio-lateral displace-
197 ment, whereas the second is positively biased by a pitch rotation with respect
198 to the IVC axis (both problems are not visible from the corresponding view,
199 respectively).

200 Figures 4-6 show the overall results from the entire dataset, considering
201 the same IVC movements as in the specific examples in Figures 1-3, respec-
202 tively. The dynamics of the IVC is quite complex, as different translations
203 and rotations occur simultaneously and together with the variation of size.
204 Moreover, IVC movements and size variation are usually correlated, as they
205 are both related to the respiratory cycle. Thus, to try to bring out the pos-
206 sible effect of specific movements on the diameters estimated from long and
207 short axis views, they were referred to the value computed by the new algo-
208 rithm (applied to X-plane US scans), that compensates their effects. Thus,
209 the percentage error, given in either (1) or (2), is plotted versus the different
210 movements.

211 Specifically, Figure 4 shows a scatter plot for each of the 8 subjects. The
212 percentage error of the estimate of the diameter in long axis is given for each
213 frame of the videos as a function of the relative medio-lateral displacement
214 of the IVC from its centre with respect to the transverse diameter. Notice
215 that a relative displacement was shown, as a dimensional translation (i.e.,
216 given in mm) has a different effect depending on the size of the cross-section.
217 Considering also that the diameter of the IVC can vary substantially between
218 subjects and due to IVC collapsibility, only displacements relative to IVC size

219 can fairly demonstrate their effect.

220 In Figure 5, the percentage error in the estimation of the diameter from
221 the short axis view is shown in scatter plots (one for each subject) versus
222 the pitch angle in radians (with zero corresponding to a tilt line orthogo-
223 nal to the IVC axis). A positive bias in the estimation of IVC size from
224 short axis is expected when the pitch angle is further from zero. Note that
225 there is sometimes an offset, which indicates an error even when the pitch
226 angle is close to zero. Since the short-axis view does not have access to
227 the longitudinal cross-section information, there may be changes outside the
228 cross-section plane that account for the observed bias. For example, the null
229 pitch condition could apply when the IVC is shifted to a region where it is
230 on average larger or smaller than its average size in the region analysed by
231 the 3D approach.

232 In Figure 6, scatter plots for each subject are shown with the longitudinal
233 translation (mm) on the x-axis (considering as positive the translations to-
234 ward the region in which the dimension of the IVC was larger in the average
235 across the frames of the echography) and on the y-axis the percentage error
236 in the estimation of the diameter from the short axis view.

237 Figure 7 shows the ranges of the three different movements and the max-
238 imum errors observed in the subjects. Respiratory cycles are the principal
239 cause of IVC movement, with the greatest excursion range occurring between
240 inspiration and expiration. We expect that the maximum errors occur at the
241 maximum excursions of the movements: this is the rationale of relating the
242 maximum errors with the range of movements. Parameters were computed
243 as 90% percentiles (after removing outliers), to get robust estimations.

244 The pitch angle has never been documented before: it is a small rotation,
245 but it can have a discreet effect when taking measurements with a short axis
246 view. The median maximal errors are around 17% for the long axis measure-
247 ment affected by a medio-lateral movement; when using the short axis view,
248 it is about 7% and 9% for the pitch angle and cranio-caudal translation, re-
249 spectively. The median cranio-caudal and medio-lateral translations were 15
250 and 4 mm, respectively, and the median pitch angle was 0.12 rad.

251 The repercussions of using a 2D scan (in long or short axis view) instead
252 of a 3D scan (X-plane view) on the estimation of parameters of clinical in-
253 terest are shown in Figure 8. As already noticed in the first figures, the IVC
254 diameter tends to be underestimated in long axis view, whereas it is overes-
255 timated when using the short axis view (both variations with respect to the
256 X-plane estimation are statistically significant, according to the Wilcoxon
257 signed rank test; notice that the diameter estimated in short axis is always
258 the largest, giving high significance in paired comparisons). The collapsibil-
259 ity indexes appear to have less consistent variations, even if in the average
260 there is a small (not significant) positive bias in measuring the CI and RCI
261 in long axis view versus the 3D approach. The estimations by the long axis
262 view of CI and RCI have also a quite large variation with respect to using
263 the 3D information provided by the X-plane view. In fact, the range of the
264 differences is about 20% (notice that the median CI is about 25% and 33%
265 for the X-plane and long axis views, respectively, with the result that the
266 uncertainty is a rather large amount of the value to be measured). Instead,
267 the range of differences in CI and RCI estimations is about 10% for the short
268 axis view. The CCI shows lower estimation differences, but also the range of

269 values to be measured is smaller.

270 **Discussion**

271 IVC shows large movements during respiration, as it is attached to the
272 diaphragm and adhered to other tissues. Moreover, the skin surface over
273 which the probe is placed is also affected by large respirophasic movements.
274 Achieving the US scan of a particular area during the respiratory cycle can
275 be challenging. In fact, while B-mode visualisation and image processing
276 techniques can compensate for in-plane movements, the 3D geometry and
277 movements of IVC can also develop partly outside the scanned view.

278 In this paper, we used the visualization in X-plane to detect and compensate
279 the IVC spatial orientation and movements. Using the X-plane as reference,
280 we documented the measurement errors expected in simple 2D visualization
281 (in either short or long axis).

282 Figure 1 clearly shows the effect of the medio-lateral translation on the di-
283 ameter estimated from the longitudinal view. The effect of this movement
284 can be mitigated when integrating information from the short axis view. It is
285 mainly caused by breathing, as the abdomen (on which the probe is placed)
286 is moving, so that it is not easy to maintain the IVC axis on the 2D longitu-
287 dinal plane, by manually adjusting the probe orientation. In fact, the IVC is
288 collapsing at the same time in which it is moving, so that it is not easy from
289 a long axis view to discriminate if the size changes are attributable only to
290 collapsibility or to a medio-lateral displacement.

291 In the lower graph of Figure 1, the diameters estimated from the three dif-
292 ferent sources are almost the same at point 1 (when the tilt plane in the

293 transverse plane is close to the centre of the cross-section), but there are
294 some differences at point 2. In fact, at the second selected point, the trans-
295 verse section line was close to the vein wall. If the movement is greater
296 than the cross-section radius, it can also cause the vein to disappear in the
297 longitudinal view (leading the operator to suspect a complete collapse).

298 An important pitch rotation of the IVC in the plane of the long axis is
299 seen only in few subjects involved in this study. However, its effect is clearly
300 that of deforming the visualized cross-section. For example, in the ideal case
301 in which the IVC is a cylinder with circular section, the visualized cross-
302 section is an ellipse with larger eccentricity as the angle increases. Figure 2
303 shows this problem, considering two frames in which the short axis section
304 is either close or far from being orthogonal to the IVC axis.

305 The cranio-caudal movement of IVC is the most evident during respira-
306 tion, as the vein is attached to the diaphragm. However, it has an important
307 effect on the estimation of IVC size from the cross-section only if the vein
308 presents substantial size changes along its length (or if it is associated to a
309 pitch rotation). Figure 3 shows an example of IVC with size changes along
310 its course: as the short axis section is fixed, the cranio-caudal movement
311 causes the US plane to intersect the vein at different sites, thus producing
312 only apparent size changes. The integration of the information from the two
313 sections allows the new algorithm based on X-plane view to compensate for
314 this problem.

315 From the quantitative point of view (Figures 4-6), the detected medio-
316 lateral (Figure 4) and cranio-caudal movements (Figure 6) are compatible
317 with [11]. The pitch angle, however, was never documented in the litera-

318 ture.

319 The interpretation of the results must be done with caution, as the different
320 movements and size variations occur together and may be correlated. In ad-
321 dition, it is possible that some frames were taken out of the plane (i.e., at a
322 yaw angle), causing the reference algorithm (based on the X-plane view) to
323 also fail. In fact, in few cases, the results were different from those expected.
324 However, the average behaviour across subjects is in line with our expecta-
325 tions, easily interpreted in simulated conditions [21], i.e., underestimation of
326 the diameter in long axis in case of medio-lateral translation and overestima-
327 tion in short axis for large pitch angles and cranio-caudal translations toward
328 a region in which the IVC is larger. This is found in the overall results shown
329 in Figure 7. It summarises the magnitude of each movement investigated,
330 showing the distribution of the values observed on the subjects included in
331 the study. The three movements are considered in different panels, showing
332 the scatter plots of the maximal percentage error versus the range of move-
333 ments and the boxplots of each variable. The median errors (about 17%
334 for the long axis measurement with medio-lateral movement; 7% and 9% in
335 short axis for pitch angle and cranio-caudal translation, respectively) indi-
336 cate some limitations in the accuracy with which the size of the IVC can be
337 estimated using a single ultrasound section. This could have implications for
338 the repeatability of measurements [13]. We expect that the observed errors
339 could depend on the operator and on the subject (as indicated by the large
340 ranges of variation), as they reflect different factors, as the IVC anatomy
341 and the relative motion between the IVC (affected by the modality of res-
342 piration, tissue compliance, etc.) and the probe (handled by an operator

343 trying to accommodate abdomen movements during respiration). However,
344 in the average, the errors have consistent dependencies on the movements,
345 which are in line with the results of the theoretical part of our work [21].
346 In simulations, each movement could be considered separate from the oth-
347 ers, one at a time, documenting its pure effect; in experimental data, other
348 concomitant motions or deformations can obscure the interpretation of the
349 results. However, still our experimental results confirm the simulations. In
350 fact, it is clear that the estimation of IVC size is affected by movements not
351 identifiable in a single plane of view. Thus, caution in the interpretation of
352 measurements is recommended when measuring IVC using a 2D view. It is
353 hoped that the increased use of US systems for X-plane visualization and 3D
354 estimation will help to reduce errors and to limit measurement variability,
355 which is still the most important limitation of this noninvasive assessment of
356 IVC.

357 The problems in measuring IVC size using 2D US visualizations are re-
358 flected into the estimation of collapsibility indexes (as CI, RCI and CCI).
359 The largest variability is found in the estimation of CI and RCI, that are
360 directly affected by the respiratory cycle. Our data show some variability
361 in the estimations, but not statistically significant differences with respect
362 to the assessment in X-plane, nor a clear trend or bias. In fact, movements
363 and size variations are correlated: thus, depending on the relative position
364 of the probe and the IVC, the contributions to size changes from movement
365 and respiration-induced pressure variations could add up or be in counter-
366 phase. This introduces variations in the estimation of caval indexes from
367 the different views which are not consistent across different subjects. This

368 could justify in part the poor repeatability of collapsibility assessment of IVC
369 documented in the literature [13].

370 Given the problems in estimating IVC dynamics from 2D views (either in
371 long or short axis), the 3D approach could be a potential useful alternative
372 (if systems that provide visualization in the X plane become widespread).
373 Assessing its benefits is left for future investigations. For example, it would
374 be interesting to test the possible improvements in the definition of the clin-
375 ical picture (e.g., in diagnosing the volume status or measuring the right
376 atrial pressure) or the repeatability of the estimates obtained using the new
377 algorithm processing the X-plane view.

378 **Conclusions**

379 The evaluation of IVC size from longitudinal and transverse views are
380 affected by the vein movements that cannot be observed in the plane of
381 the US scan. The problem can be mitigated by integrating the information
382 from the two planes, synchronously acquired by an US system in X-plane.
383 Specifically, the algorithm introduced in the article, previously published,
384 is able to compensate for medio-lateral translation, mean longitudinal axis
385 pitch and longitudinal translation. It was used as reference to document the
386 effect of those movements in limiting the accuracy in evaluating IVC size and
387 collapsibility in experimental data from single tilt sections. Specifically, this
388 study for the first time simultaneously quantifies 3 movements of the IVC
389 on experimental US scans and confirms the implications on the errors that
390 characterize the 2D assessments.

391 **Conflict of interest**

392 An instrument implementing the 2D algorithms used in this paper was
393 patented by Politecnico di Torino and Università di Torino (patent number
394 WO 2018/134726) and was taken in license by VIPER s.r.l.

395 **Data Availability Statement**

396 Data are available from the corresponding author upon reasonable re-
397 quest.

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481 **Figure Captions**

482 **Figure 1:** Estimation of the diameter of the inferior vena cava (IVC) in
483 subject 5 in which the vein makes a large medio-lateral movement. The
484 top panels display two X-plane echography images of IVC, in which the
485 long axis section is taken either close to the centre of the cross-section
486 (left) or close to the border (right). The time course of the diameter
487 is shown in the bottom panel, estimated from the longitudinal and
488 transverse views and by integrating their information. Two arrows, in
489 the bottom graph, indicate the times in which the frames shown on top
490 occurred. A small diameter is estimated from the long axis view when
491 the medio-lateral translation is large.

492 **Figure 2:** Estimation of IVC diameter in subject 4 in which the vein makes
493 an in-plane rotation. The top panels display two X-plane echography
494 images of IVC, in which the angle between the short axis section and
495 the vein is small (left) or close to 90° (right). The time course of the
496 diameter is shown in the bottom panel, estimated from the longitudinal
497 and transverse views and by integrating their information. Two arrows,
498 in the bottom graph, indicate the times in which the frames shown on
499 top occurred. The diameter estimated from a short axis view has a
500 positive bias when the angle is smaller.

501 **Figure 3:** Estimation of IVC diameter in subject 1 in which the vein has
502 large variations of the section in its long axis course. The top panels
503 display two X-plane echography images of IVC, in which the translation
504 of the vein makes the short axis section be taken either where it is

505 smaller (left - cranial direction) or larger (right - caudal). The time
506 course of the diameter is shown in the bottom panel, estimated from the
507 longitudinal and transverse views and by integrating their information.
508 Two arrows, in the bottom graph, indicate the times in which the
509 frames shown on top occurred. In this case, the diameter estimated
510 from a short axis view has a positive bias when the IVC moves in
511 caudal direction.

512 **Figure 4:** Percentage error of the diameter derived from the longitudinal
513 section relative to the equivalent diameter recovered from IVC volume
514 estimation, shown as a function of the medio-lateral translation. All
515 frames and subjects are considered. The x-axis shows the ratio of the
516 medio-lateral translation with respect to the tilt line to the diame-
517 ter calculated from the transverse section. The linear interpolation is
518 shown by a red line and the range defined by the standard error is in-
519 dicated by a red dotted line, after removing the outliers. The identifier
520 of the subjects, the standard error, and the slope of the interpolation
521 line are indicated in the title.

522 **Figure 5:** Percentage error of the diameter derived from the transverse sec-
523 tion relative to the equivalent diameter recovered from IVC volume
524 estimation, shown as a function of the absolute value of the pitch an-
525 gle. All frames and subjects are considered. The x-axis shows the
526 pitch, in radians, with respect to the perpendicular tilt line. The linear
527 interpolation is shown by a red line and the range defined by the stan-
528 dard error is indicated by a red dotted line, after removing the outliers.

529 The identifier of the subjects, the standard error, and the slope of the
530 interpolation line are indicated in the title.

531 **Figure 6:** Percentage error of the diameter derived from the transverse sec-
532 tion relative to the equivalent diameter recovered from IVC volume es-
533 timation, shown as a function of longitudinal translations. All frames
534 and subjects are considered. The x-axis shows the longitudinal trans-
535 lations with respect to the tilt line (mm). The linear interpolation is
536 shown by a red line and the range defined by the standard error is in-
537 dicated by a red dotted line, after removing the outliers. The identifier
538 of the subjects, the standard error, and the slope of the interpolation
539 line are indicated in the title.

540 **Figure 7:** Range of movements and percentage errors (ErrL and ErrT indi-
541 cating the error when using the long and short axis view, respectively)
542 observed in different subjects (scatter plots of a pair of variables and
543 boxplot of each variable). A) Error in the estimation of the diameter
544 from the long axis view over the medio-lateral translation. For each
545 subject, the maximal error (outlier excluded) and the maximal trans-
546 lation in mm are considered. A scatter plot and a boxplot of each
547 variable are shown. B) Error in the estimation of the diameter from
548 the short axis view over the pitch angle (same format as in A). C) Er-
549 ror in the estimation of the diameter from the short axis view over the
550 cranio-caudal translation.

551 **Figure 8:** Estimation of IVC parameters (i.e., mean diameter, caval index
552 (CI), respiratory caval index (RCI), and cardiac caval index (CCI)),

553 using US scans in X-plane (3D), long axis view (2D long) and short axis
554 view (2D short). A) Individual parameters (mean diameter, CI, RCI
555 and CCI) estimated from each subject using the 3 methods (3D, 2D long
556 and 2D short). Statistical differences were found for the measurement
557 of the diameter (* $p < 0.05$ and ** $p < 0.005$) B) Box and whiskers plots
558 (showing median, quartiles, range, and outliers) of the estimations of
559 the parameters with the 3 methods. C) Box and whiskers plots of
560 the difference in the estimations of the parameters when using the 2D
561 methods instead of the 3D one.

Figure 4

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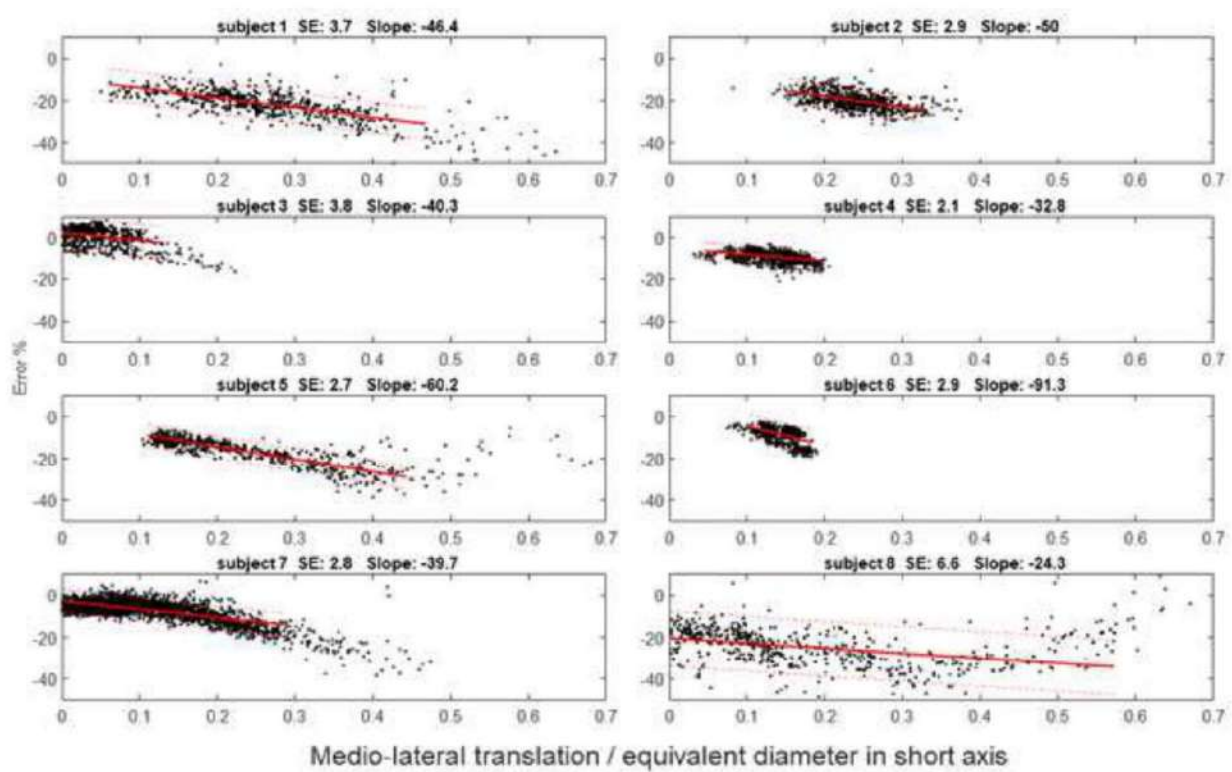


Figure 5

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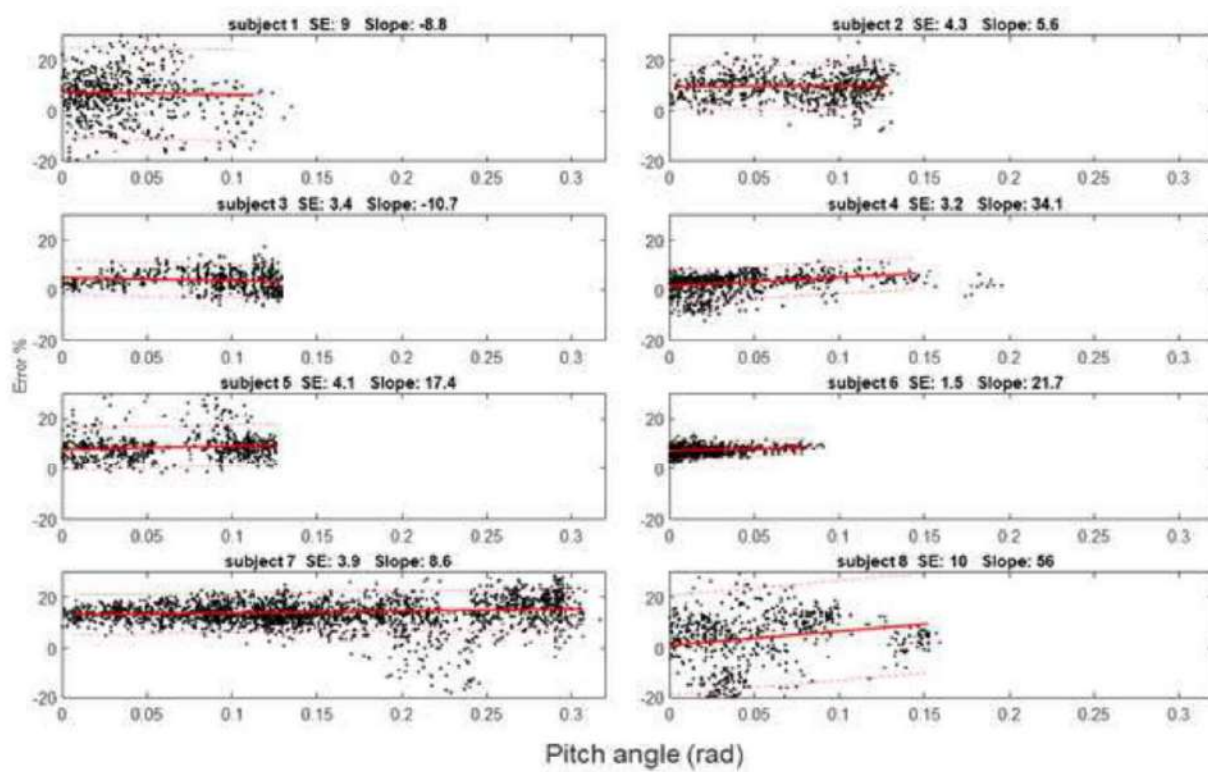


Figure 6

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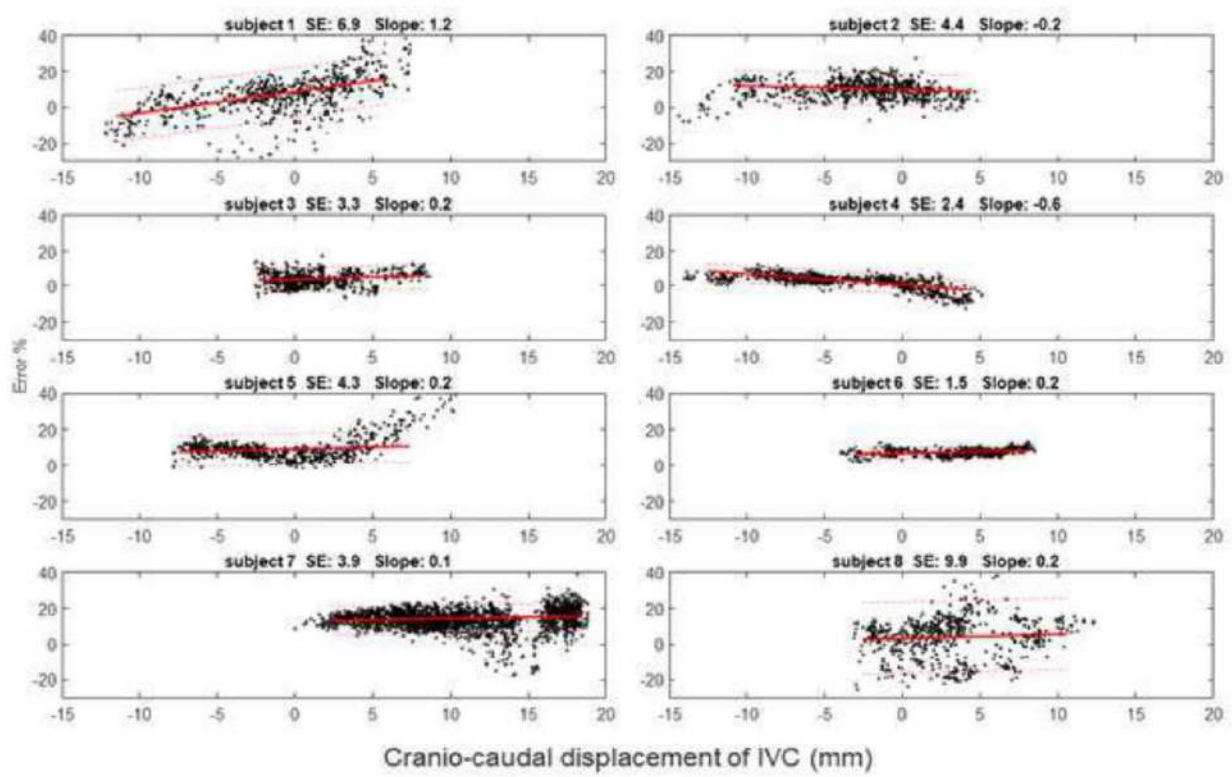


Figure 7

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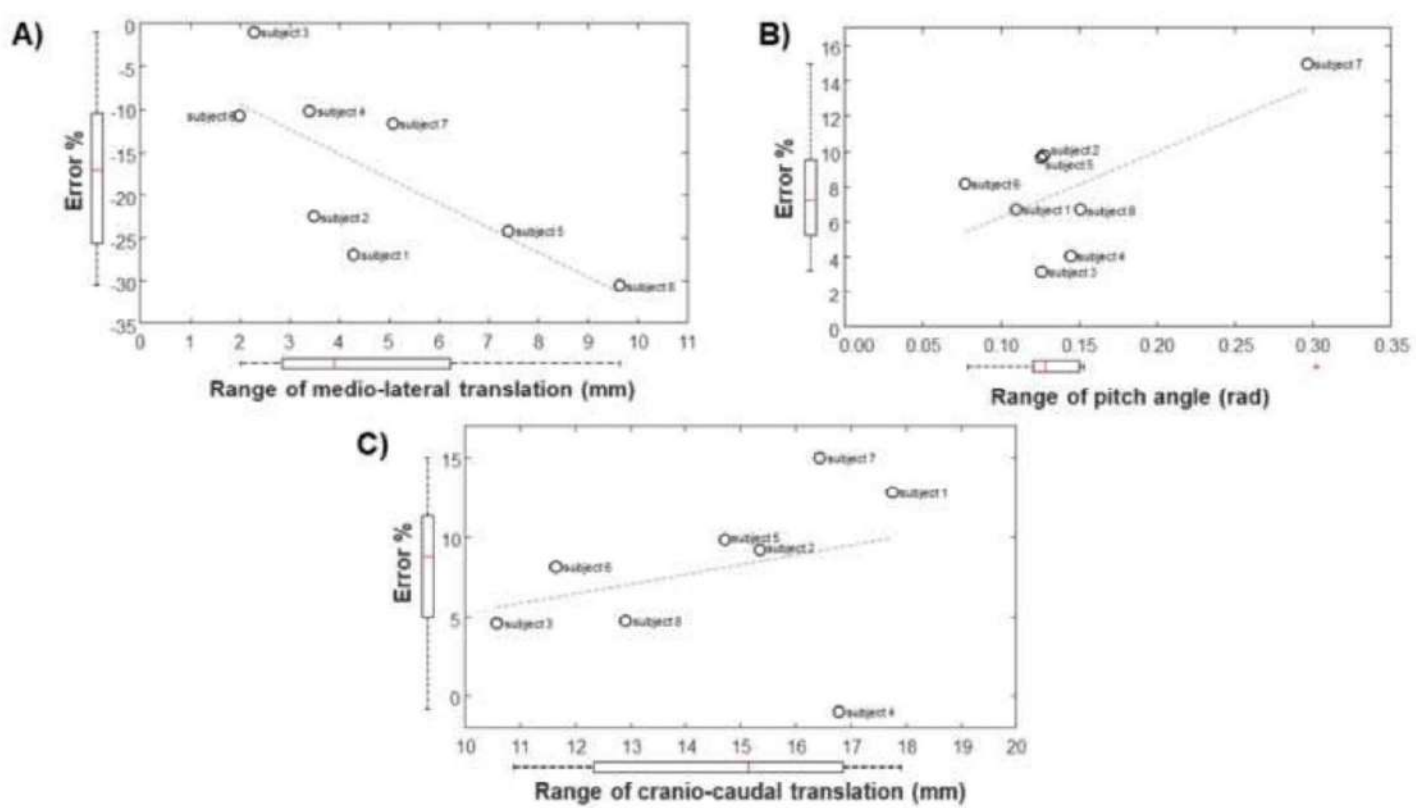


Figure 8

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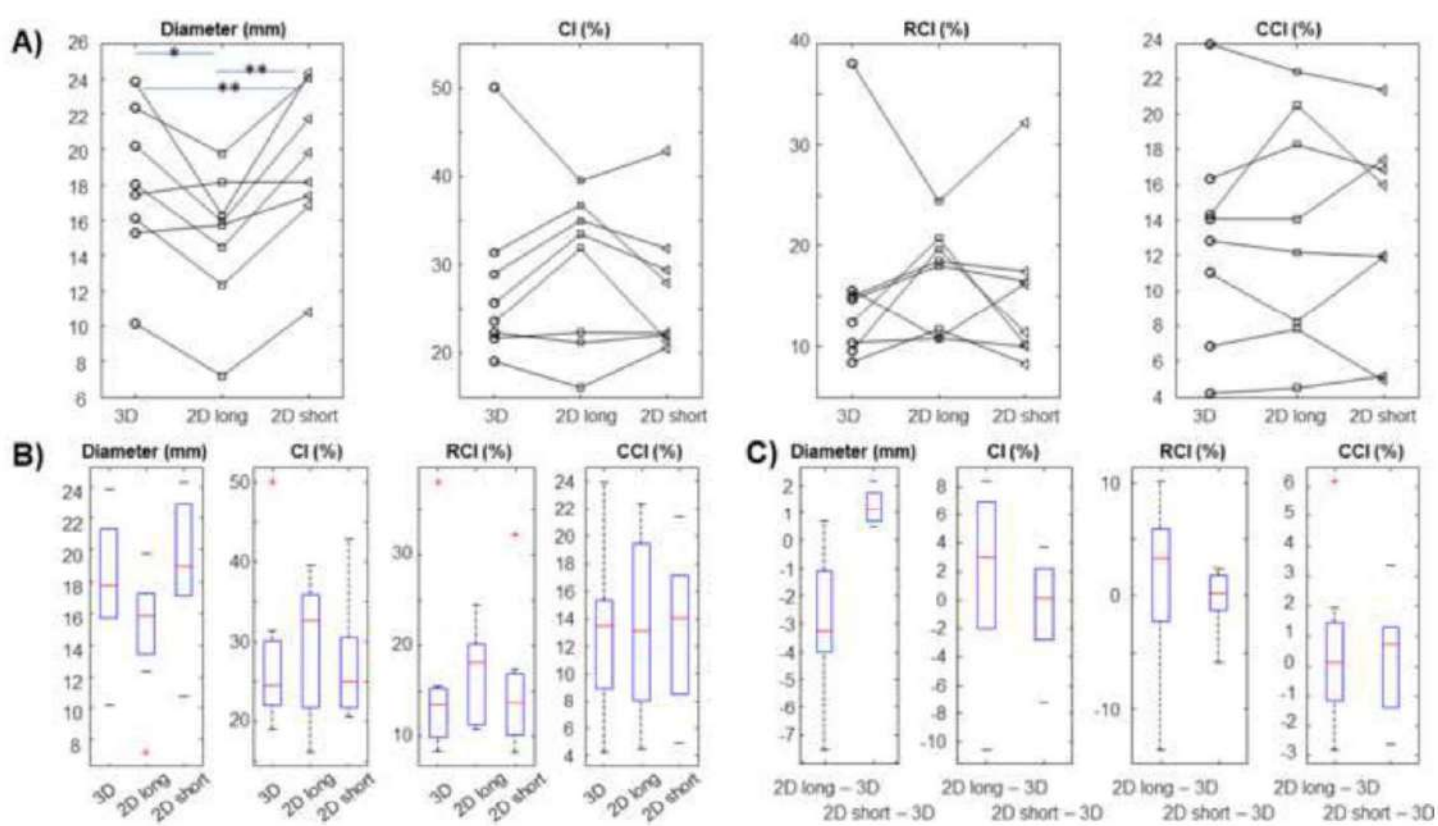


Figure 2

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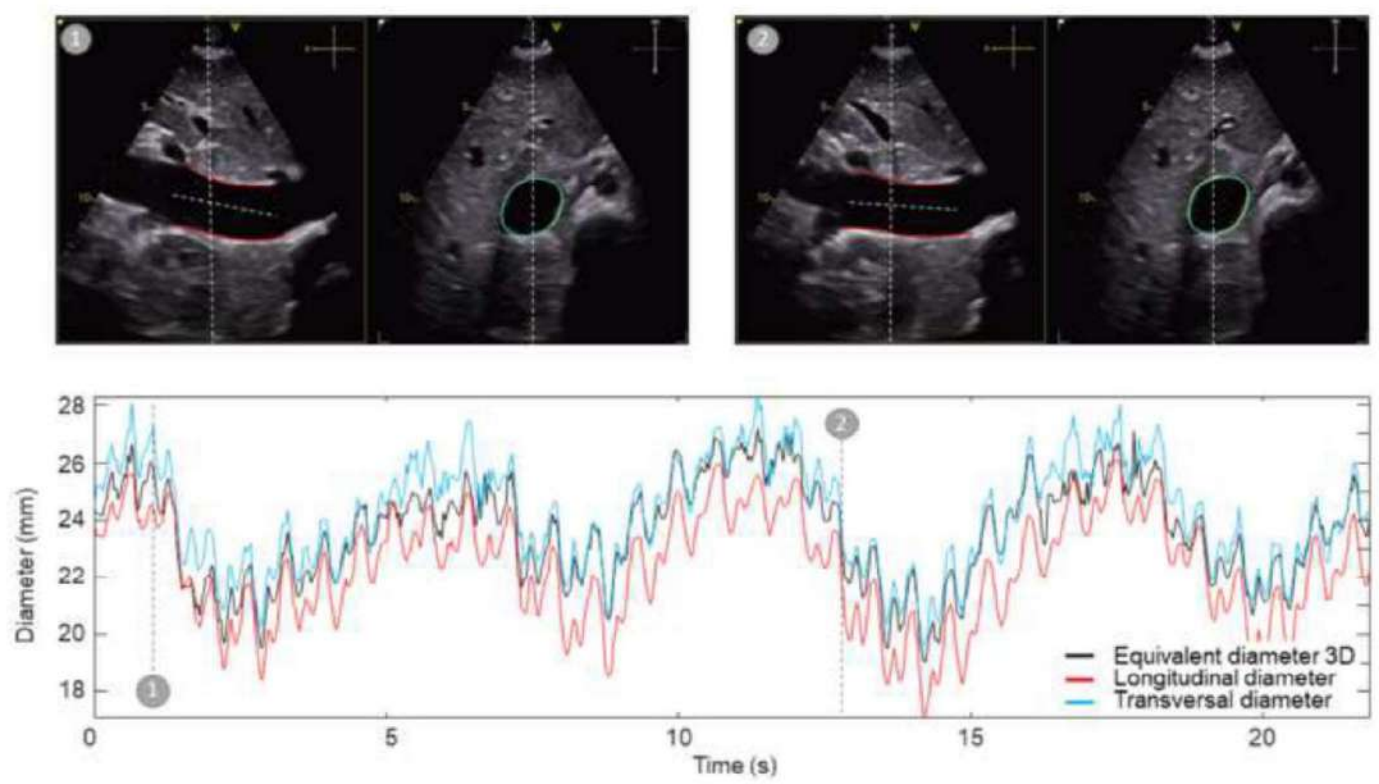


Figure 3

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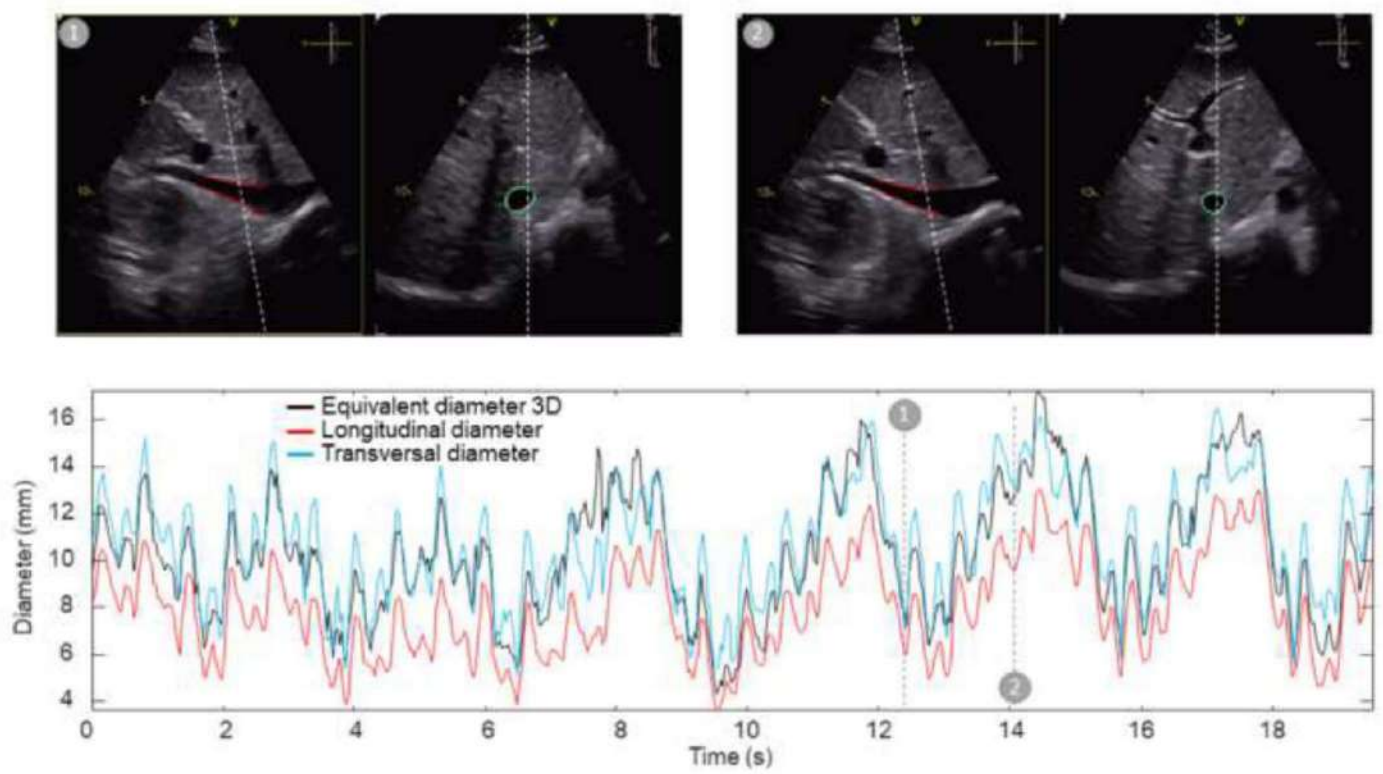


Figure 1

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