Simulation of cardiac output determination with dynamic contrast-enhanced computed tomography for definition of optimal settings

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Purpose

The determination of the cardiac output (CO) is a relevant diagnostic marker in various diseases with heart involvement\cite{1,2}. We used a software phantom to estimate the accuracy of a CO determination from dynamic contrast-enhanced computed tomography (CT) images of the thorax\cite{3} and study influences of various imaging settings and haemodynamics. Particularly we considered the reduced cardiac output and slow blood flow through the heart and pulmonary vasculature in patients with severe impairment of the blood flow\cite{1,2}. To keep the expected radiation exposure as low as possible we limited our simulation to 20 CT images over time.
Methods and Materials

We simulated the dynamic CT sequence by creating a software phantom with attenuation values taken from a representative thorax CT slice at the height of the pulmonary artery. In this image we defined the regions of the large vessels and the lung parenchyma, as well as the regions of interest (ROIs) for our CO determination. Choosing haemodynamic parameters typical for patients with different severity of disease\(^{[1,2]}\), we simulated CT sequences with the corresponding attenuation changes in the respective regions. Further we created a sinogram from each image, added Poisson and Gaussian distributed noise, and reconstructed the images to also include noise and streak artefacts in the simulation. From this sequence we extracted the mean Hounsfield units in the ROIs and fitted these curves with a gamma-variate function using a Levenberg-Marquardt algorithm\(^{[4-6]}\). From these fits we calculated the blood flow in the large vessels using indicator-dilution theory\(^{[7]}\) (Fig. 1). The results for the central pulmonary artery and the ascending aorta are reported here. The ROIs of these two vessels were circles with a radius of 16 pixels each.

We varied the time increments between the individual images from 1 s to 2 s therefore covering 20 to 40 s. This is necessary to monitor a bolus passage from entry at the vena cava to the exit at the descending aorta in patients with different disease severity. Further we simulated the slower bolus passage by delaying the boluses by fixed factors ranging from 1 to 2, mimicking severe impairment of the blood flow.

Extravasation or partial blocking of the subclavian vein due to the patient's arm position in the CT scanner can lead to the retention of some contrast material on the way from the injection site to the heart\(^{[8]}\). To simulate the effect of a delayed bolus passage by retaining 10 or 20 % of contrast material and subsequent release, we reduced the attenuation curve by the respective percentage and added a second one with the retained amount of contrast material but a 2.5 times longer time to peak.

Additionally we evaluated the influence of a total-variation based denoising algorithm on the CO determination\(^{[9]}\).

The applied COs were 2.67, 3.80 and 4.65 l/min and the mean absolute errors of the calculated COs were determined over 50 individual simulation runs.
**Fig. 1:** Schematic depiction of simulation algorithm from the representative CT image to the simulated dynamic CT sequence with noise and artefacts

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Results

The relative error of the CO calculations for all simulations stayed constant for all input COs. This allows a more accurate CO determination in the regime with higher clinical relevance. Varying the time increment between individual images from 1 to 2 s did not change the mean error. We found the mean error to be below 1 % in all ROIs (Fig. 2). Likewise the slowed down bolus by factors between 1 and 2 does not change the mean absolute error of the calculation in the pulmonary artery but a small increase could be observed in the aorta. Still the errors stayed below 1 % of the input CO (Fig. 3). Therefore we conclude that the sampling intervals can be chosen freely to accommodate for the slower bolus dynamics in patients with severe impairment of the blood flow.

The partial retention of contrast material had the biggest effect on the error. Retention of 10 or 20 % and delayed release of the contrast material lead to a systematic overestimation of the CO on average by 8 and 15 %, respectively (Fig. 4). This indicates that proper contrast material injection and patient positioning in the CT scanner is necessary to avoid extravasation or blockage of the contrast material bolus.

Denoising of the images by a total-variation based algorithm had no influence on the CO determination in the ROIs (Fig. 5). Therefore this algorithm can be used without affecting the calculation accuracy.
**Fig. 2:** Results of simulations varying the time increment between individual CT images; Top: Change in attenuation over time and time point of images with increasing time increments for the central pulmonary artery; Bottom: Mean absolute error of the simulation for the three simulated cardiac outputs and time increments

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Fig. 3: Results of simulations varying the time to peak of the contrast material bolus; Top: Change in attenuation over time and factor increasing time to peak for the central pulmonary artery; Bottom: Mean absolute error of the simulation for the three simulated cardiac outputs and factors increasing time to peak for time increments of 2 s

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**Fig. 4:** Results of simulations varying the proportion of retained contrast material; Top: Change in attenuation over time and proportion of retained contrast material for the central pulmonary artery; Bottom: Mean absolute error of the simulation for the three simulated cardiac outputs and proportion of retained contrast material for time increments of 2 s

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Fig. 5: Results of simulations varying the time increment between individual CT images with and without denoising; Top: Exemplary images without and with denoising; Bottom: Mean absolute error of the simulation for the three time increments with and without denoising for an input cardiac output of 3.80 l/min

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Conclusion

Dynamic contrast-enhanced thorax CT scans can be used to evaluate the cardiac output with an error smaller than 1 % using 20 consecutive images with 1 to 2 s between them and gamma-variate fitting of the attenuation curves. However care has to be taken, that the contrast material is not extravasated or that the arm veins are not obstructed by the patient's positioning in the CT scanner.
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