Assessment of a simple method of heart weight estimation by postmortem computed tomography

INTRODUCTION

Postmortem computed tomography (PMCT) provides a noninvasive method for the documentation of whole-body data and the detection of bone and visceral lesions before autopsy. PMCT is increasingly being used as an alternative or adjunct to conventional autopsy. Provided that organ weights are important when investigating the cause of death at autopsy, several studies have reported the use of PMCT to estimate organ weights.

It has been reported that PMCT can accurately estimate lung [1] and liver [2] weights. If heart weight can also be accurately measured by PMCT, it will help with investigations into cause of death, because an increased heart weight is a key disease marker (e.g., valvular disease and cardiomyopathies) [3, 4]. However, it is difficult to calculate heart weight directly from PMCT. This was because blood is known to have varied attenuations in the heart cavity on PMCT, making it difficult to distinguish from cardiac muscle [5]. In other words, heart weight estimated from whole heart weight (including pooling blood) may be inaccurate. Other studies have reported that left ventricular circumferential area (LVCA) on CT or magnetic resonance imaging (MRI) reflects actual heart weight [6, 7].

In our study, we tested two hypotheses for estimating heart weight by PMCT. First was that estimation of heart weight based on LV (left ventricle) weight is more accurate than whole heart weight. We believed that LV weight would reflect actual heart weight in the same way as LVCA. The second

hypothesis was that a simplified estimation of heart weight using LV as an ellipsoid would be as reliable as a more demanding segmentation-based estimation. It is possible to estimate whole LV weight by summing the weight of each region of interest (ROI), which contoured the LV on each CT slice. However, such an approach is cumbersome. The clinical ultrasound (US) approach is to measure LV cavity volume based on three axes, with the assumption that the cavity is an ellipsoid. Therefore, we hypothesized that we could estimate whole LV weight using these three axes on PMCT together with the myocardial specific gravity.

The aims of this study were thus to test the following hypotheses: 1. LV-based estimation of heart weight is more accurate than whole heart assessment; and 2. a simplified ellipsoid LV-based estimation of heart weight is similarly reliable as the more demanding segmentation-based estimation.

MATERIALS AND METHODS

Study Design and Subjects

This was a retrospective study of 33 consecutive postmortem cases that underwent both PMCT and autopsy between February 2008 and June 2014 at Niigata City General Hospital. There were no other inclusion or exclusion criteria. The institutional review board of Niigata City General Hospital approved the study and waived the need for prior informed consent.

Autopsy Procedure

Two board-certified pathologists performed pathological autopsies within 24 hours of death and immediately following PMCT. The heart weight excluding blood was measured at autopsy: hearts

were opened according to a standard procedure, and blood and clots were washed out. All epicardial fat and approximately 1 cm of the aortic and pulmonary arteries were included.

CT image acquisition

CT images were obtained using two multidetector-row CT scanners (either a SOMATOM Sensation16 or a SOMATOM Definition AS; Siemens Healthineers, Elragen, Germany). Non-contrast enhanced images were used for this study. The scanning parameters for PMCT were as follows: tube current, automatic exposure control; tube voltage, 120 kVp; detector pitch, 0.6 mm; detector collimation, 64 × 0.6 mm; gantry rotation time, 0.5 s; field of view, 350 × 350; pixel spacing, 512 × 512. CT image reconstruction was performed with a slice thickness of 2 mm, using soft tissue-weighted tissue kernels.

Image analysis

The acquired PMCT image data were transferred to a personal computer and image analysis was performed by a radiologist with 8 years' experience, using ImageJ [8]. Three measurements of heart weight were taken for analysis.

(1) PMCT1: Whole heart weight

Whole heart weight (including pooling blood in the cardiac cavity) was calculated from the heart volume and CT attenuation value on PMCT. The regions of interest (ROIs) were set by manually contouring the heart on all axial sections from the ascending aorta (3 cm above the aortic valves) to the bottom of the heart (see Figure 1 for a representative image) [9]. Consequently, the mean CT

attenuation values (Hounsfield units, HU) and areas of slice each were measured. Weight was calculated from each slice area, thickness, and mean CT attenuation, using the following formula [10]: weight (g) = 1.006 × (mean CT attenuation value + 1000) × volume (cm^3) / 1000. The whole heart weight, including pooling blood in the cardiac cavity, was calculated by summing the weight of each slice.

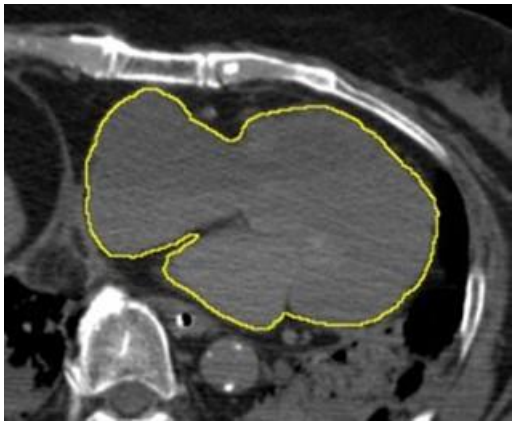


Figure 1. The regions of interest were set by manually contouring the heart on all axial sections (from 3 cm above the aortic valves to heart apex) in PMCT and measuring the area and mean CT attenuation

(2) PMCT2: Whole LV weight

The whole LV weight (including pooling blood in the LV cavity) was calculated from the LV volume and the CT attenuation value on PMCT. ROIs were set by manually contouring the LV on all axial sections from the level of the aortic valve to the cardiac apex on PMCT (see Figure 2 for a representative image). The whole LV weight, including pooling blood in LV cavity, was calculated by summing the weight of each slice calculated from the area, thickness, and mean CT attenuation, as above.

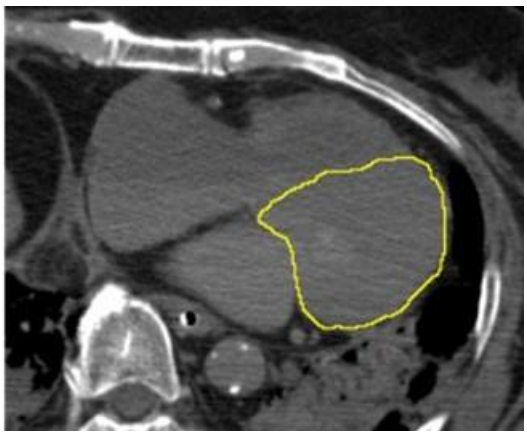
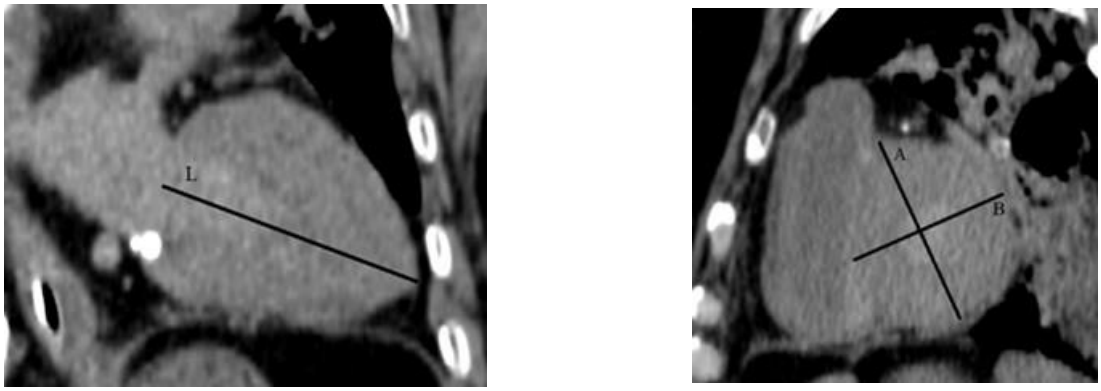


Figure 2. The regions of interest were set by manually contouring the LV on all axial sections from the aortic valve to the cardiac apex on PMCT and measuring the area and mean CT attenuation

(3) PMCT3: Estimated heart weight (ellipsoid model)

We calculated the estimated LV weight from the estimated ellipsoid volume on PMCT. For this, we reconstructed the LV vertical long-axis and the short axis views from the PMCT images. The longer LV axis (L cm) was measured as the line from the cardiac apex to the mitral valve annulus on the LV vertical long-axis view (see Figure 3a for a representative image). The other two axes were measured as the longer diameter (A cm) and shorter diameter (B cm) on the maximum section of the LV short axis view (see Figure 3b for a representative image). The estimated LV volume was then calculated as follows: ellipsoid volume (cm^3) = $4/3\pi \times A/2 \times B/2 \times L/2$. However, because we could not measure the mean CT attenuation values of the LV by PMCT, we used the myocardial specific gravity (1.05 g/cm^3) [11]. The estimated LV weight was calculated by multiplying the estimated ellipsoid LV volume by the myocardial specific gravity.



(a) (b)

Figure 3. (a) The LV long-axis (L) is measured as the line from the cardiac apex to the mitral valve annulus on the LV vertical long-axis view. (b) A is the longer diameter and B is the shorter diameter on the maximum section of the LV short axis view. L, A, and B are recorded in centimeters.

Statistical analysis

Statistical analysis was performed using Dr.SPSS II. Using linear regression analysis, the heart weight (excluding blood) measured by autopsy was compared with the whole heart weight (including pooled blood in the cardiac cavity) calculated from PMCT1 and the whole LV weight (including pooled blood in the LV cavity) calculated from PMCT2. In addition, linear regression analysis was used to compare the estimated (ellipsoid) LV weight on PMCT3 with the heart weight measured at autopsy, and the whole LV weight (including pooled blood in LV cavity) calculated from PMCT2. The linear regression results are reported using the coefficient of determination (R^2), the standard error (SE), the regression coefficients and their 95% confidence intervals (95%CI), and the linear regression equations. Student's t-test was used for comparing the heart weight estimated from whole LV weight and the estimated LV weight. *P* values < 0.05 were considered statistically significant.

RESULTS

Subjects

We studied 33 consecutive cases (20 men and 13 women) that underwent PMCT and autopsy during the study period. The mean age ± standard deviation was 63.00 ± 20.5 years, and the age range was 6–87 years. The causes of death were acute myocardial infarction or ischemia (n = 10), malignant neoplasm (n = 4), aortic dissection (n = 3), sepsis (n = 2), intestinal necrosis (n = 3), bleeding (n = 2), pneumonia (n = 1), pulmonary embolism (n = 1), epilepsy (n = 1), intracerebral hemorrhage (n = 1), Parkinson's disease (n = 1), sarcoidosis (n = 1), myocarditis (n = 1), and unknown (n = 2).

Weight measurements in autopsy and PMCT

The mean heart weight (excluding blood) was 381.55 ± 130.23 g. The mean values for the whole heart weight, whole LV weight, and estimated LV weight were 504.50 ± 201.02 g, 174.40 ± 78.10 g, and 150.48 ± 67.49 g, respectively.

Linear regression equations

PMCT1: Whole heart weight

The linear regression equation between heart weight excluding blood at autopsy (Y g) and whole heart weight including blood calculated from PMCT (X g) was Y = 0.47X + 142.73 (Figure 4). This model explained 53% of the heart weight, the SE was 90.34, and the regression coefficient was 0.47 (95%CI: 0.31–0.63; $P < 0.05$).

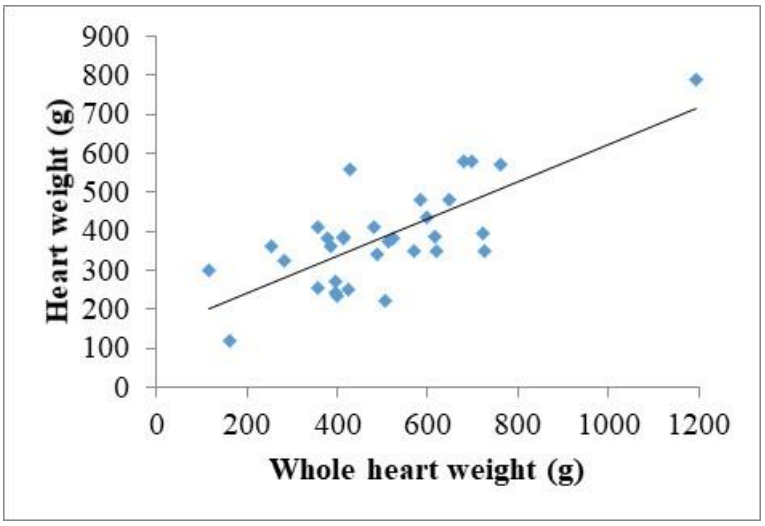


Figure 4. Linear regression of the relationship between heart weight excluding blood by autopsy (Y g) and whole heart weight including blood by PMCT (X g): $Y = 0.47X + 142.73$ ($R^2 = 0.53$).

PMCT2: Whole LV weight

The linear regression equation between heart weight excluding blood measured by autopsy (Y g) and whole LV weight including pooling blood in the LV cavity calculated from PMCT (Z g) was $Y = 1.46Z + 125.83$ (Figure 5). This model explained 77% of the heart weight, the SE was 63.01, and the regression coefficient was 1.46 (95%CI: 1.17–1.75; $P < 0.05$).

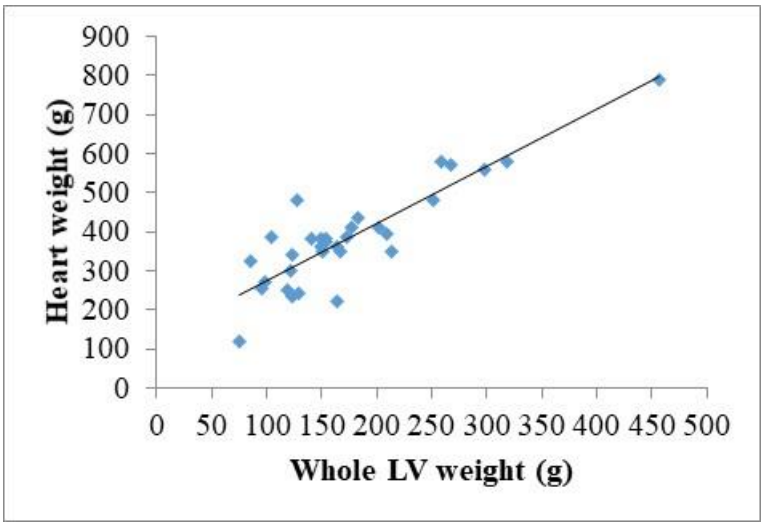


Figure 5. Linear regression of the relationship between heart weight by autopsy (Y g) and whole LV weight including blood in the LV by PMCT (Z g): $Y = 1.47Z + 125.83$ ($R^2 = 0.77$).

PMCT3: Estimated LV and heart weights (ellipsoid model)

The linear regression equation between heart weight excluding blood measured by autopsy (Y g) and estimated LV weight (ellipsoid model) on PMCT (Q g) was $Y = 1.64Q + 134.77$ (Figure 6). This model explained 72% of the heart weight, the SE was 69.73, and the regression coefficient was 1.64 (95%CI: 1.27–2.01; $P < 0.05$).

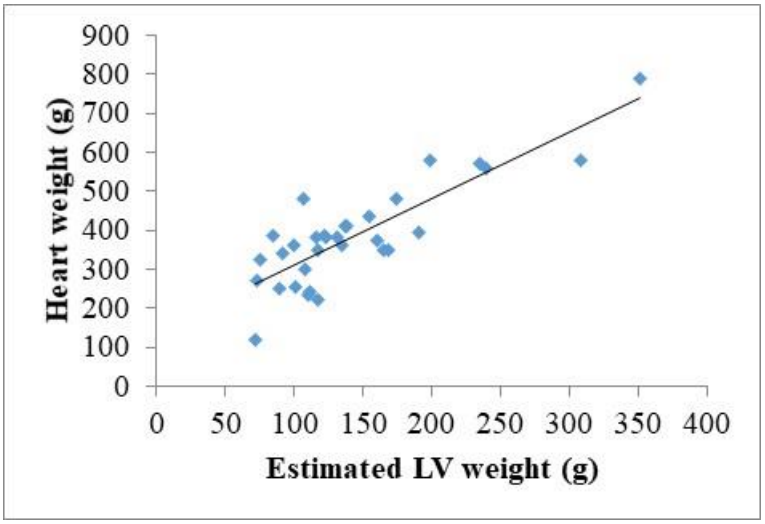


Figure 6. The relationship between the heart weight excluding blood measured by autopsy (Y g) and the estimated LV weight (Q g). The solid line was linear regression equation: $Y = 1.64Q + 134.77$ ($R^2 = 0.72$).

The linear regression equation between the whole LV weight including pooled blood in the LV cavity calculated from PMCT (Z g) and the estimated LV weight (ellipsoid model) on PMCT (Q g) was $Z = 1.11Q + 7.06$ (Figure 7). Interestingly, this model was most effective and explained 92%

of the heart weight. The SE was 21.94 and the regression coefficient was 1.11 (95%CI: 0.99–1.23; $P < 0.05$).

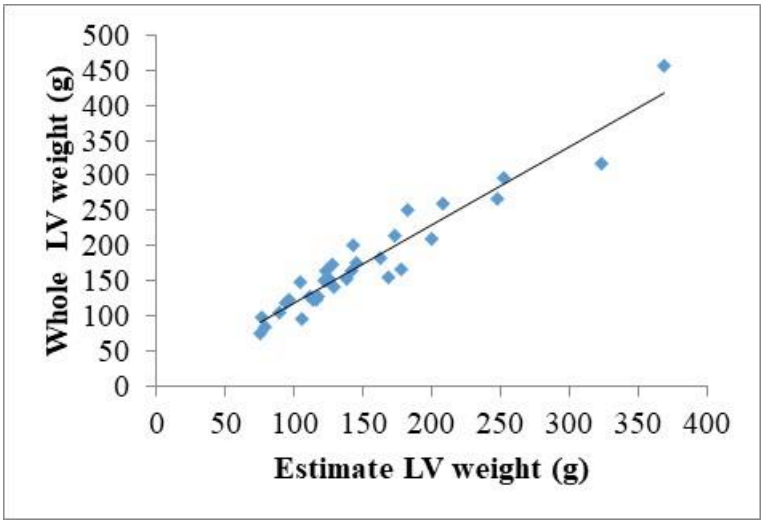


Figure 7. The relationship between the whole LV weight including pooling blood in LV cavity (Z g) and the estimated LV weight calculated from PMCT (Q g). The solid line was linear regression equation: $Z = 1.11Q + 7.06$ ($R^2 = 0.92$).

No significant difference was noted between the heart weight estimated from the whole LV weight and the estimated LV weight ($p > 0.05$).

DISCUSSION

Heart weight can be predicted to varying degrees by age, sex, body height, body weight, body mass index, and body surface area. In cases without cardiovascular disease, body surface area is considered the best predictor of cardiac weight among these (R^2 = 0.83–0.88) [12-14]. When cardiovascular disease is present; however, heart weight estimates based on body surface area tend to become inaccurate (R^2 = 0.16–0.56) [15] because heart weight changes in the presence of such disease [3, 4]. By contrast, even in cases with cardiovascular disease, heart weight can be predicted accurately

from PMCT because the morphometry data are of the heart itself. S. Winklhofer et al. investigated whether the cardiothoracic ratio in PMCT was reliable for identifying cardiomegaly [16]. It had been proposed that LVCA on CT reflects actual heart weight, but LVCA on CT-based estimation of heart weight was inaccurate ($R^2 = 0.61$) [6]. Although LVCA on MRI-based estimation was accurate ($R^2 = 0.78$) [7], access is more restricted than in CT and it is difficult to perform postmortem MRI.

Our estimates of heart weight based on the whole heart weight (including pooled blood in the cardiac cavity) were inaccurate when calculated from the PMCT data ($R^2 = 0.53$). We anticipate that this was because the volume of pooled blood in the cardiac cavity affected the total heart weight, with previous studies showing that the blood volume in the heart cavity can range from 8 to 550 mL [9, 17]. In contrast to this, the heart weight could be estimated with reasonable accuracy from the whole LV weight (including pooled blood in the LV cavity) when calculated from the PMCT data ($R^2 = 0.77$). One reason for this may be that the LV weight can be assumed to account for most of the heart weight because the LV wall and the interventricular septum are about four times thicker than those of the right ventricle [18]. Another reason could be that the LV wall is thick and the LV cavity contracts relative to the right ventricle and atrium after death due to the disappearance of the blood pressure gradient [19, 20]. Thus, the effect of pooling blood in the LV on LV weight might be less than the effect of pooling blood in the heart on heart weight.

Finally, we showed that our simple method of estimating heart weight without the need to set ROIs was accurate. Assuming that the LV had an ellipsoid shape, we calculated the LV weight by

multiplying the estimated LV volume by the myocardial specific gravity, which was based on the area–length method used to measure LV cavity volume on US assessment. In our method, we assumed that the outer shape (rather than the cavity) of the LV was an ellipsoid. As a method of measuring the LV cavity volume, the area–length method has been considered inaccurate in US because the cavity is not a smooth ellipsoid [21]. However, we showed that there was a strong correlation between the estimated LV weight and the whole LV weight ($R^2 = 0.92$) and no significant difference between the heart weights estimated from estimated LV weight and whole LV weight. This may have been because the outer wall of the LV was relatively smooth and free of papillary muscle, approximating the ellipsoid shape more closely. Moreover, the heart weight measured by autopsy could be predicted from this estimated LV weight ($R^2 = 0.72$) and there was no significant difference between the heart weight estimated from whole LV weight and estimated LV weight. We thus propose that our method is an uncomplicated way to estimate heart weight.

This simple method can be used to predict heart weight prior to autopsy or to give a reasonable estimate of heart weight. This may be useful if PMCT is used by forensic pathologists as a screening tool for medico-legal autopsies or by forensic radiologists as a method to assess cardiomegaly without autopsy. The sensitivity and specificity of the heart weight estimated from the LV weight in detecting cardiac-related deaths requires further study.

Limitations

Our study has several limitations. First, only one radiologist performed image analysis and

the autopsies were performed in a single institution. However, the autopsy and heart weight measurements were performed by standard methods. Furthermore, ROIs were set by an experienced radiologist, and it is known that the outer wall of the heart and LV can be distinguished easily from epicardial fat, which is unlikely to be different on PMCT. Second, the number of cases in our study was small and we did not include any cases with severe cardiac malformations. We assume that our method would not be applicable in the case of severe cardiac (LV) malformation (e.g., a single ventricle or a hypoplastic left heart) because the LV weight would not comprise most of the heart's weight. Further studies are needed to investigate the effectiveness of our methods in various disease states. Third, in the heart cavity, there may be cardiovascular gas due to cardiopulmonary resuscitation (CPR) or putrefaction [22]. In our method for estimating heart weight from PMCT3 (estimated LV weight), the estimated heart weight is heavier than the heart weight by the volume of cardiovascular gas in the LV cavity. The effects of putrefaction can be minimized by performing PMCT immediately after death. The effect of cardiovascular gas by PCR must be considered when estimating heart weight. If the amount of gas in the heart appears large, it is necessary to use the method for estimating heart weight from PMCT2 (whole LV weight). Fourth, to estimate the specific gravity from the CT attenuation value, it is necessary to estimate the ratio of the number of atomic units per electron for the investigated material to water. For soft tissue, 1.006 is a reasonable estimate with error rate of 1% [10]. In our study, 1% is an acceptable error range.

Conclusion

In this research, we have proposed and assessed a new method for estimating the heart weight at autopsy based on the heart and LV weights calculated from data on three PMCT axes. The proposed method is a simple and useful way to estimate heart weight.

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