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Surface Models of the Four Chambers in Young Adult Hearts with Average Volumes Measured by Artificial Intelligence Tools

Modelos de Superficie de las Cuatro Cámaras en Corazones de Adultos Jóvenes con Volúmenes Promedio Medidos Mediante Herramientas de Inteligencia Artificial

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SUMMARY: The average volumes of normal heart chambers in computed tomography (CT) are used not only as clinical criterions for heart disease diagnosis, but also as references in cardiology. With the development of artificial intelligence (AI), numerous CT data can be analyzed and segmented automatically. This study aimed to determine the average volumes of the four chambers in healthy adult hearts and present surface models with the average volume. Coronary CT angiographs of 508 Korean individuals (330 men and 178 women, 20 – 39 years old) were obtained. An automatic segmentation module for 3D Slicer was developed using machine learning in Anatomage KoreaTM. Using the module, the four chambers and heart valves in the CT were segmented and reconstructed into surface models. Surface models of the four chambers of identical hearts in the CT were produced using SimplewareTM. The volumes of structures were measured using Sim4life Light and statistically analyzed. After determining the average volumes of the four chambers, surface models of the average volumes were constructed. In both software measurements, the atrial volumes of females increased with age, and the ventricular volumes of males decreased significantly with age. The atrial and ventricular volumes of Simpleware were larger and smaller than those of Anatomage, respectively, because of errors in the Simpleware. Regarding the volume measurement, our module developed in this study was more accurate than the Simpleware. The average volume and three-dimensional models used in this study can be used not only for clinical purposes, but also for educational or industrial purposes.

KEY WORDS: Heart; Cardiac Volume; Adult; Segmentation; Computed Tomography; Artificial Intelligence.

INTRODUCTION

The average volumes of the four heart chambers (right atrium, right ventricle, left atrium, and left ventricle) in healthy adults have been used in various medical fields (Kerkhof *et al*., 2018; Mandoli *et al*., 2019). Anatomically, average volumes can be used as criteria for diagnosing morphological changes in the heart chambers (Haugaa *et al*., 2016). Physiologically, it is used as a reference to analyze the ability of motor performance in the heart to distinguish normal from diseased states (Guzzetti *et al*., 2020). In cardiology and cardiac surgery, it is used to design artificial chambers for the heart, left ventricle assist devices, and blood circulation devices (Ali *et al*., 2020). To verify the feasibility of these medical devices for the heart, stability and performance tests need to be simulated virtually using three-dimensional (3D) heart models with an average heart volume.

Many studies have been conducted on heart chamber volume (Kerkhof *et al*., 2018; Mandoli *et al*., 2019; Gao *et al*., 2022). However, most studies have focused on the left ventricle rather than the entire chamber because of its role in pumping blood into the systemic circulation (Rigolli *et al*., 2016; Scollan *et al*., 2016; Ko *et al*., 2019). In some studies, the volumes of the chambers were measured, but the volumes were obtained from different people (Kawel-Boehm *et al*., 2020) or from middle-aged or more (40 - 84 years old) (Fuchs *et al*., 2016). However, the four chambers of the heart are systematic structures because an identical amount of blood flows from the atrium to the ventricle or from left to right during systole and diastole. In addition, the chamber volumes of young people are required to investigate the optimal motor performance of the heart.

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Therefore, the volumes of the four chambers obtained from a young person should be investigated.

Meanwhile, to measure the average volume of each chamber, the hearts of several healthy young adults should be examined. The best method to meet these needs is computed tomographic imaging (CT), which is more accessible than the expensive and time-consuming magnetic resonance imaging (MRI). In Korea, many CT scans of healthy young adults could be taken because most Koreans receive medical checkups regularly, including CT for free or low cost at a hospital by virtue of public medical insurance.

Organ volumes on CT are mostly measured using the workstation of the CT scanner (Fuchs *et al*., 2016). However, a CT workstation is generally available only to authorized people, and the CT workstation and its software are more difficult to use than a personal computer. Fortunately, automatic segmentation and 3D reconstruction software using artificial intelligence (AI) for personal computers have recently been released (Morris *et al*., 2020), but suitable software for checking heart volume could not be found.

The purpose of this study was to present the average volumes of the four chambers in the hearts of young adults and to provide 3D models with an average volume of the four chambers. Furthermore, we introduced optimal AI tools that enable the automatic segmentation of the chambers in the heart. For this purpose, coronary CT angiographs of 508 healthy young adults (20 - 39 years old) were processed using AI tools, and their 3D models of average volumes were produced.

MATERIAL AND METHOD

After the entire process of this study was approved by the institutional review board (AJIRB-MED-MDB-21-417), coronary CT angiographs in the end-diastolic phase of 508 people (330 men and 178 women) aged 20 - 39 years were obtained from an university hospital in Korea. We used coronary CT angiograph scans obtained during regular medical checkups. CT scans showing abnormal or pathological lesions were excluded from the study. Body mass index was cited from Size Korea (http://sizekorea.kats.go.kr) projects performed by Korean Agency for Technology and Standards in this study (Kim *et al*., 2017).

To segment the four chambers of the heart and related structures on coronary CT angiograph, we used two software packages.

First, we used a 3D Slicer 5.0.3 (https://www.slicer.org) with an automatic heart segmentation module. The module on the 3D slicer was self-produced by Anatomage Korea INC (Seoul, Republic of Korea). In the first step, four chambers and four valves in the heart CT scans of 50 randomly selected individuals were segmented manually by Anatomage developers. The segmented images were used as answer sheets for AI machine learning in the PyTorch framework (Muñoz-Aguirre *et al*., 2020; Thomas *et al*., 2021). The trained artificial intelligence was modularized for use in a 3D Slicer for the automatic segmentation of four chambers and four valves in heart CT.

After installing the Anatomage_module in the 3D Slicer, four chambers and four valves in the heart CT of 508 people were automatically segmented using the Heart CT Segmentation Tool in the module. From the segmented images, the surface models were reconstructed and saved in stereolithography (STL) format on a 3D Slicer.

Second, we used Simpleware ScanIP (Synopsys®, Exeter, UK) with the AS_cardio_module, which is a commercial software. On Simpleware ScanIP, the four chambers of the hearts of 508 individuals were automatically segmented using the Heart CT Tool with the module. Surface models were reconstructed from the segmented chambers using the Export Tool and saved in STL format.

To measure the volume of the surface models, we used Sim4life Light (Zurich MedTech AG, Zurich, Switzerland), in which the volume of the surface model can be measured easily and quickly. The volumes of the four chambers and related structures in the surface models (STL files) from the Anatomage and Simpleware modules were measured using the Geometry Tool on Sim4life Light.

The average volume of each structure was calculated based on the measured volumes. All structural volumes were statistically analyzed using GraphPad Prism 8.0 (GraphPad Software, San Diego, CA,).

Among the surface models of 508 hearts, we selected the surface models that had the closest size to the average volumes of the four chambers in twenties and thirties. The size of the surface models was modified to correspond to the average chamber volumes measured with the Anatomage_module using the Scale Tool in Autodesk Maya 2024 (Autodesk Inc., San Rafael, CA, USA). To maintain the original shape during volume modification, the scale of the surface models was proportionally revised along three axes (length, width, and height). After scaling the surface models, the volumes were checked repeatedly using Sim4life Light until the volume difference was <1 %. Volume-modified surface models of the four chambers were assembled into a Portable Document Format (PDF) file using Deep Exploration 6.3 (SAP America, Inc., Newton Square, PA, USA).

Ethics Approval. This study was approved by the institutional review board (AJIRB-MED-MDB-21-417).

RESULTS

The volumes of the four chambers (right atrium, RA; right ventricle, RV; left atrium, LA; left ventricle, LV) in the hearts were acquired from the CT scans of 508 healthy adults aged 20 - 39 years (330 men, 178 women) using AI tools. Using the Anatomage_module, the four chambers in the heart and four additional heart valves (mitral, tricuspid, aortic, and pulmonary valves) were automatically segmented on the 3D Slicer. Using the AS_cardio_module, the four chambers and five additional structures (myocardium, ascending aorta, pulmonary artery, and right and left coronary arteries) were automatically segmented on Simpleware ScanIP (Fig. 1; Table I). Furthermore, the surface models of the four chambers with average volumes measured by Anatomage_module were produced (file formats, STL; file size, 232 Mbytes) (Fig. 2). Four set (twenties and thirties for both sexes) of surface models were placed in a PDF file (30.3 Mbytes) for easy distribution and accessibility.

Comparison of four heart chamber volumes

Volumes of the four heart chambers were analyzed according to sex and age. There was no significant difference in the volumes of male atrial chambers between twenties and thirties. In female atrial chambers, thirties were significantly bigger than twenties (RA and LA in Anatomage, $P<0.05$; RA in Simpleware, $P<0.05$) except LA of Simpleware (Fig. 3; Table I). The volume of male ventricular chambers in thirties was significantly smaller than twenties (RV in Simpleware, $P<0.001$; LV in Simpleware, $P<0.001$; RV in Anatomage, $P<0.01$; LV in Anatomage, $P<0.001$) (Fig. 3; Table I). In female ventricular chambers, only the RV in thirties was significantly smaller than twenties (Simpleware, $P<0.01$); however, there was no significant difference in other female ventricular chambers. Consequently, the atrial volume of women increases with age, and the ventricular volume of men decreases with age. According to other studies, ventricular volumes decrease due to an increase in ventricular wall thickness with age (Peverill, 2021; Woulfe & Walker, 2021).

The volumes of the four chambers in the heart were analyzed according to type of software. In atrial chamber volumes, Simpleware was significantly larger than Anatomage for all ages and both sexes ($P<0.001$, Fig. 4) because Simpleware segmented not only the atrium but also the vena cava and pulmonary vein (Fig. 1). In the volumes of LV in all data and RV in women in their twenties, Anatomage was significantly larger than Simpleware in both sexes ($P<0.001$, Fig. 4) because Anatomage segmented the LV at the boundary of the closed mitral valve, unlike

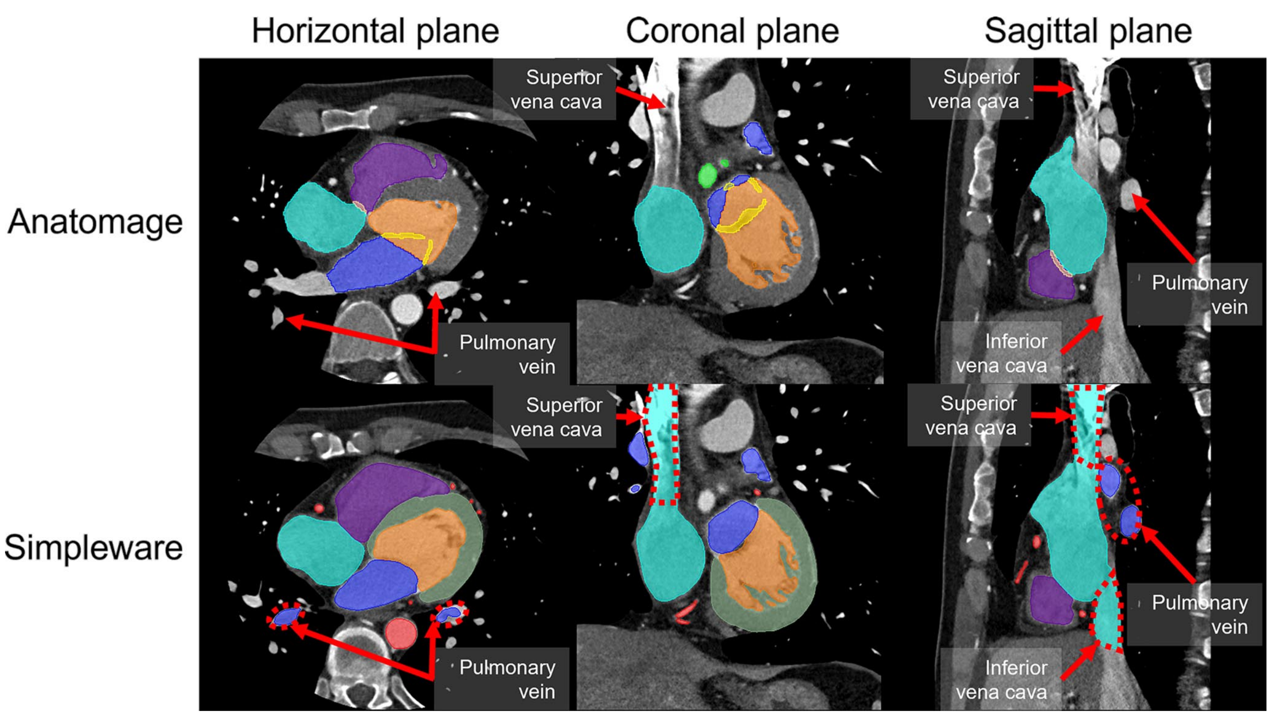

Fig. 1. Segmented heart chambers on CT processed in the Anatomage_module (top) and AS_cardio_module of Simpleware (bottom). Only the right atrium is segmented (azure) on the Anatomage_module (top), whereas the right atrium, superior vena cava, and inferior vena cava are segmented (azure) on Simpleware (bottom). Right atrium (azure), right ventricle (purple), left atrium (blue), left ventricle (orange), myocardium (light green), pulmonary valve (green), mitral valve (yellow), and arteries (red).

Table I. Body mass index from Size Korea (Kim *et al*., 2017) and mean (standard deviation) volumes of four chambers and valves in hearts and arteries, measured in coronary CT angiographs of 508 healthy adults using CT segmentation modules (Unit, cm^3).

		20 - 29 years old		30 - 39 years old		
Body mass index from Size Korea (Kim *et al*., 2017)		23.95[a], 24.74[b]	21.19[a], 21.88[b]	25.59[c], 25.77[d]	21.77[c], 22.1[d]	
Structures	Module maker	139 males	57 females	191 males	121 females	Total 508 people
Chamber of right atrium*	Anatomage	74.20 (16.56)	52.00 (11.29)	75.34 (17.59)	56.54 (12.77)	68.02 (18.26)
	Simpleware	99.30 (19.03)	72.78 (12.11)	100.09 (19.54)	78.41 (13.4)	91.65 (20.62)
	Kawel-Boehm ***	46.00 (16.00)	35.00 (9.00)	46.00 (16.00)	35.00 (9.00)	/
Chamber of right ventricle**	Anatomage	172.78 (29.29)	132.54 (23.50)	163.09 (28.87)	127.15 (17.85)	153.81 (32.15)
	Simpleware	171.01 (27.59)	130.24 (17.42)	160.75 (26.69)	123.29 (16.62)	151.21 (30.82)
	Kawel-Boehm ***	163.00 (27.00)	127.00 (24.00)	163.00 (27.00)	127.00 (24.00)	/
Chamber of left atrium*	Anatomage	59.58 (11.38)	46.74 (9.99)	61.07 (13.12)	50.74 (10.01)	56.62 (12.79)
	Simpleware	83.09 (14.13)	64.22 (10.64)	84.27 (16.19)	67.15 (11.47)	77.62 (16.36)
	Kawel-Boehm ***	32.00 (9.00)	28.00 (7.00)	32.00 (9.00)	28.00 (7.00)	/
Chamber of left ventricle**	Anatomage	133.88 (23.75)	105.69 (18.97)	124.32 (22.63)	104.66 (13.47)	120.20 (23.81)
	Simpleware	120.89 (20.88)	98.21 (14.10)	112.06 (19.88)	95.49 (11.75)	108.97 (20.50)
	Kawel-Boehm ***	155.00 (30.00)	123.00 (22.00)	155.00 (30.00)	123.00 (22.00)	/
Myocardium	Simpleware	138.06 (24.56)	84.42 (14.76)	136.06 (22.78)	84.53 (13.12)	118.54 (32.41)
Ascending aorta	Simpleware	66.51 (13.07)	45.92 (9.72)	73.79 (15.36)	53.58 (10.28)	63.86 (16.45)
Pulmonary artery	Simpleware	42.20 (10.75)	31.95 (9.93)	44.17 (10.55)	33.28 (7.94)	39.67 (11.17)
Right coronary artery	Simpleware	1.85 (0.83)	1.00 (0.58)	2.02 (0.92)	1.15 (0.55)	1.65 (0.88)
Left coronary artery	Simpleware	2.31 (0.87)	1.17 (0.58)	2.44 (0.97)	1.30 (0.61)	1.99 (0.99)
Mitral valve	Anatomage	3.18 (0.53)	2.57 (0.31)	3.19 (0.58)	2.65 (0.44)	2.99 (0.58)
Tricuspid valve	Anatomage	3.67 (0.76)	2.90 (0.53)	3.63 (0.81)	2.94 (0.65)	3.40 (0.81)
Aortic valve	Anatomage	5.07 (1.13)	3.52 (0.86)	5.38 (1.29)	4.00 (0.86)	4.76 (1.31)
Pulmonary valve	Anatomage	4.17 (0.81)	3.09 (0.64)	4.35 (0.95)	3.45 (0.79)	3.95 (0.96)

*Minimum volume; **End-diastolic volume; ***Kawel-Boehm *et al*.; /, Not applicable; [a]20 - 24 years old; [b]20 - 25 years old; [c]30 - 34 years old; [d]30 - 35 years old

Simpleware (Fig. 1). Consequently, the atrial and ventricular volumes of Anatomage were smaller and larger, respectively, than those of Simpleware.

Automatic segmentation of the Anatomage_module was more reliable than that of Simpleware because of the error in atrial segmentation by Simpleware (Fig. 1).

Comparison of this study and the study conducted by Kawel-Boehm *et al*. (2020)

This study was compared to the study by Kawel-Boehm *et al*. (2020), who presented a comprehensive commentary on the volumes of the heart chambers. Kawel-Boehm *et al*. (2020) analyzed multiple studies of various ages using cardiovascular magnetic resonance images technique. All conditions of this study and the study conducted by Kawel-Boehm *et al*. (2020), were not identical; therefore, we compared our study and that conducted by Kawel-Boehm *et al*. (2020), only in terms of general tendencies. Because the volume in this study was measured in the end-diastolic phase, ventricular volumes in the end-diastolic phase and the atrium in the minimum size were compared. In the volumes of the atria and ventricles, differences in Anatomage of our study and that performed by Kawel-Boehm *et al*. (2020), were smaller than the difference between Simpleware and Kawel-Boehm *et al*. (2020) (Table I). Considering this trend, the volumes of Anatomage are more reliable than those of Simpleware.

DISCUSSION

In this study, the atrial volume of women was significantly increased with age (Fig. 3). According to related studies, the cause of the increase in atrial volume in both sexes is atrial fibrillation (Thomas *et al*., 2002). The ventricular volumes in this study significantly

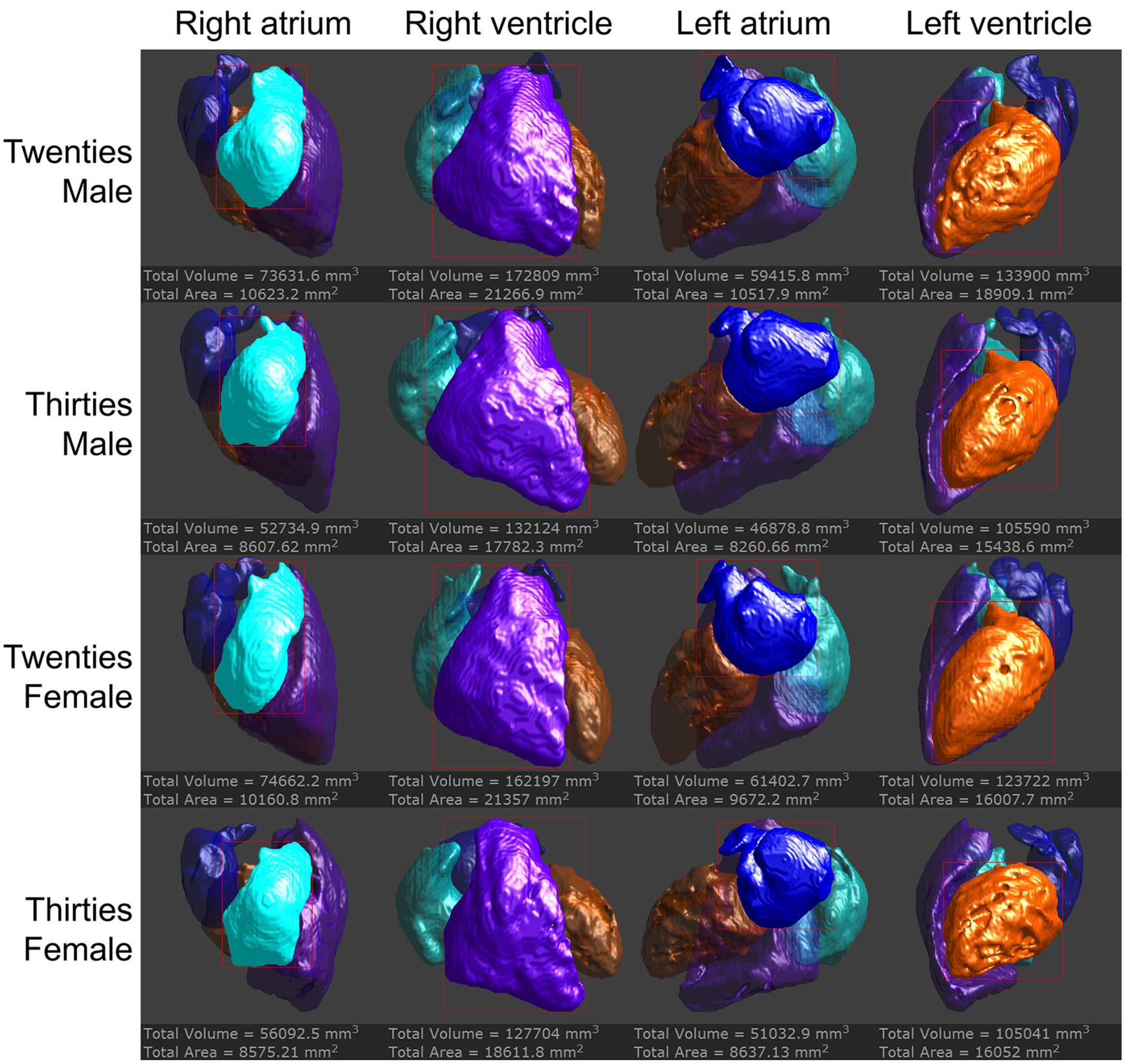

Fig. 2. Surface models of four heart chambers with average volumes using the Anatomage_module. In Sim4life Light, total volume (mm^3) and area (mm^2) of the surface models in the four chambers were measured. Right atrium (azure), right ventricle (purple), left atrium (blue), and left ventricle (orange).

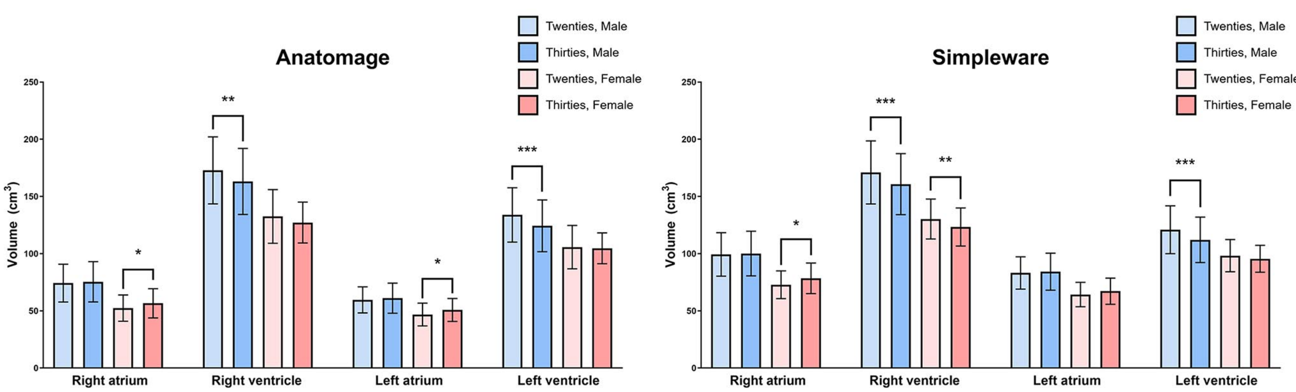

Fig. 3. Comparison of average volumes of four chambers in hearts by sex and age (*P<0.05, **P<0.01, ***P<0.001).

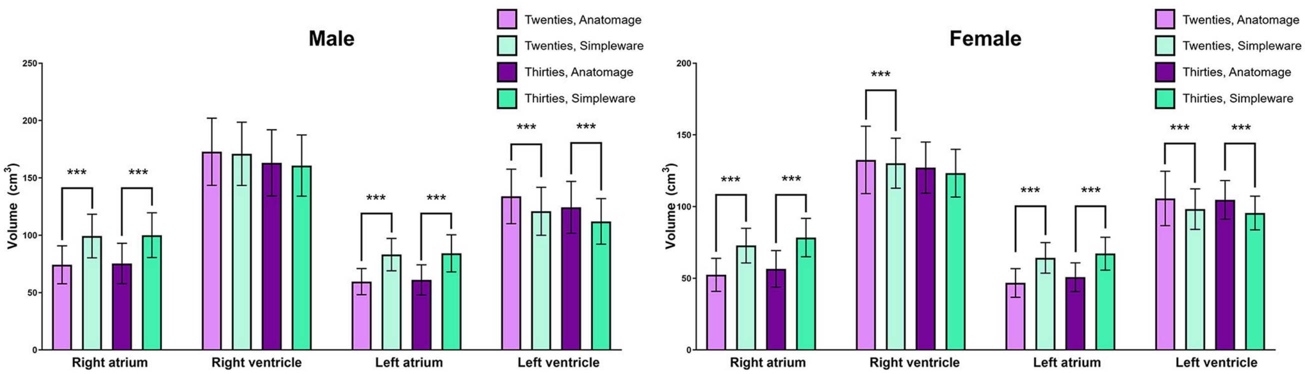

Fig. 4. Comparison of average volumes of four chambers in hearts by software (*P<0.05, **P<0.01, ***P<0.001).

decreased with age in both sexes and in both software packages (Figs. 3 and 4). According to related studies, ventricular volume decreases with age owing to structural remodeling and increased ventricular wall thickness (Peverill, 2021; Woulfe & Walker, 2021).

To study the volumes of the heart chambers, it is desirable to measure the volumes of the four chambers simultaneously because the four chambers are functionally closely related to the bloodstream. However, in most studies, the chamber volume focused on the left ventricle (Rigolli *et al*., 2016; Scollan *et al*., 2016; Ko *et al*., 2019), or the four chambers were measured by several people, and not the same person (Kawel-Boehm *et al*., 2020). Even in studies that investigated four chambers in the same population, the subjects were middle-aged or more (40 - 84 years old) (Fuchs *et al*., 2016). Therefore, we only used coronary CT angiographs in which volumes of four chambers were measured in the same young people at the same time (Fig. 1; Table I).

A limitation of this study was that height and weight factors of the individual subjects were not considered in the average volumes. To obtain exact results in the biological experiments, obese or skinniest adults and the tallest or shortest adults were excluded before the main experiment. However, we could not use height and weight data of subjects because of ethical issues. Accordingly, we focused on measuring as many CT scans as possible instead of excluding extreme bodies. To supplement heights and weights, body mass index values were cited from Size Korea project performed by the Korean government.

Automatic segmentation of structures using CT or MRI is essential for measuring the volume of a structure. The anatomical boundaries of the four heart chambers are the fibrous rings of the fibrous skeleton that surround the orifices of the valves. Therefore, we attempted to segment each chamber with fibrous rings as boundaries using the existing software. However, in most software for heart segmentation, the boundaries of the four chambers are defined by valves; therefore, no matter how good a software, such as Simpleware ScanIP is, segmentation is difficult in valveless regions, such as between the vena cava and RA and between the pulmonary veins and LA (Fig. 1). Therefore, we developed a segmentation software using AI machine learning for the segmentation of anatomical boundaries. In this study, researchers of Anatomage segmented the anatomical boundaries of four chambers in the CT of 50 individuals as correct answer sheets and a programmed automatic segmentation tool (Anatomage_module) by AI machine learning based on the answer sheets. Therefore, Anatomage was able to provide a more accurate segmentation of each chamber than Simpleware. If answer sheets fit certain segmentation purposes, computer engineers can create automatic segmentation tools for CT or MRI using AI machine learning. We recommend that users ask computer engineers to create automatic tools using AI machine learning. Then, we will be able to perform a segmentation that fits the purpose.

CONCLUSION

In this study, we found that the volume of the atrium tended to be similar in men and larger in women in both software with age, and the volume of the ventricle tended to be smaller with age (Figs. 3 and 4). Based on this volume information, the surface models of the four chambers with average volumes were constructed (Fig. 2). The average volume of the heart chambers and surface models used in this study can be used for educational, clinical, and industrial purposes. In particular, the average heart volume can be used as a reference criterion for the diagnosis of heart diseases. For medical industrial purposes, these volumes can be helpful for producing medical instruments for the heart, such as artificial hearts. Surface models of this study could be downloaded in author's homepage (Neuroanatomy.co.kr).

KIM, C.Y.; HAN, M. R.; KIM, S. Y. & PARK, J. S. Modelos de superficie de las cuatro cámaras en corazones de adultos jóvenes con volúmenes promedio medidos mediante herramientas de inteligencia artificial. *Int. J. Morphol., 42(3)*:554-560, 2024.

RESUMEN: Los volúmenes medios de las cámaras cardíacas normales en la tomografía computarizada (TC) se utilizan no sólo como criterios clínicos para el diagnóstico de enfermedades cardíacas, sino también como referencia en cardiología. Con el desarrollo de la inteligencia artificial (IA), numerosos datos de TC se pueden analizar y segmentar automáticamente. Este estudio tuvo como objetivo determinar los volúmenes promedio de las cuatro cámaras en corazones adultos sanos y presentar modelos de superficie con el volumen promedio. Se obtuvieron angiografías coronarias por TC de 508 individuos coreanos (330 hombres y 178 mujeres, de 20 a 39 años). Se desarrolló un módulo de segmentación automática para 3D Slicer utilizando aprendizaje automático en Anatomage KoreaTM. Utilizando el módulo, las cuatro cámaras y valvas cardíacas de la TC se segmentaron y reconstruyeron en modelos de superficie. Se produjeron modelos de superficie de las cuatro cámaras de corazones idénticos en la TC utilizando SimplewareTM. Los volúmenes de las estructuras se midieron utilizando Sim4life Light y se analizaron estadísticamente. Después de determinar los volúmenes promedio de las cuatro cámaras, se construyeron modelos de superficie de los volúmenes promedio. En ambas mediciones de software, los volúmenes atriales de las mujeres aumentaron con la edad y los volúmenes ventriculares de los hombres disminuyeron significativamente con la edad. Los volúmenes atrial y ventricular de Simpleware eran mayores y menores que los de Anatomage, respectivamente, debido a errores en Simpleware. En cuanto a la medición de volumen, nuestro módulo desarrollado en este estudio fue más preciso que el Simpleware. Los modelos tridimensionales y de volumen medio utilizados en este estudio se pueden utilizar no solo con fines clínicos, sino también con fines educativos o industriales.

PALABRAS CLAVE: Corazón; Volumen cardíaco; Adulto; Segmentación; Tomografía computarizada; Inteligencia artificial.

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