The heart exhibits right to left communication between the fibres of the muscular part of the interventricular septum

P.J. Kuusela

Private internist, Kuopio, Finland

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1900 years ago Galen stated that blood seeps through the perforations in the interventricular septum. However, William Harvey, working 400 years ago, failed to find any. In this study an aqueous solution of a black dye was gently pumped by hand into the right ventricle of 20 porcine hearts. The area in the middle of the left muscular part of the interventricular septum in 13 of the hearts was bloodstained under the endocardium at the time the heart stopped beating. The same area of all 20 hearts eventually became stained black. A small amount of black dye seeped through the endocardium of 18 hearts in the middle of the left muscular part of the interventricular septum. In another 20 porcine hearts the interventricular septa were dissected after boiling. The deep pit under the anterior interventricular sulcus communicated with the right ventricle and with the middle of the left muscular part of the interventricular septum between the fibres of the muscle. The communication closed tight at the very early systole. The communication resembled that reported by Galen 1900 years ago. The communication may be the real foetal route for diastolic circulation through the muscular part of the interventricular septum from right to left. The results suggested that the anatomy, function and embryology of the African monkey, human and porcine heart are not yet fully understood. (Folia Morphol 2014; 73, 1: 42–50)

Key words: heart anatomy, heart function, heart electrophysiology, heart embryology, helical heart, septal vessel, kuuselian vessel

INTRODUCTION

Some of the first branches leaving the aorta supply the heart and brain, organs that require a high concentration of oxygen for normal development. Oxygenated blood from the umbilical circulation crosses the foramen ovale into the left atrium.

Pulmonary venous blood, which represents about 8% of total cardiac output, mixes with oxygenated blood. This blood then represents about 35% of the total foetal cardiac output. These figures are obtained from the studies in chronically instrumented close-to-term foetal lambs. The more recent Doppler velocity evaluation suggests in human right ventricular (RV) cardiac output dominance 57%. The blood pressures in the main pulmonary trunk and RV are 1–2 mm Hg higher than those in the aorta and left ventricle (LV) [9].

The sinoatrial node initially activates the right atrium, followed by the activation of the left atrium 6 to 10 ms later [7]. In most cases the left His bundle has 3 fascicles: anterior, posterior and septal. The activation of the middle third of the septum occurs
A congenital VSD of the heart may appear in any part of the septum [3]. A single VSD of the left central muscular part of the IVS may present with numerous sieve-like perforations through the right muscular part of the IVS formed from the medial wall of the foetal RV [2]. A small hole in the membranous part of the IVS becomes a hidden communication through the membranous part of the IVS as the aneurysm of the membranous part of the IVS grows over the hole on the right side after birth [10, 13].

Galen was born in 130 A.D. and studied medicine for 11 years in Egypt [11]. He boiled and dissected hearts. He also dissected living animals (vivisection), particularly African monkeys and vivisected the LV. He saw the blood flows out of the coronary veins and arteries of the anterior interventricular sulcus and right to left through the central muscular part of the IVS. Galen stated they could be found exactly by carefully dissecting a freshly-killed animal. The force behind arterial pulsation has its origin in the heart. Liquid from the stomach is absorbed into the veins. Galen stated that blood passes from the RV through the parenchyma of the lungs into the LV and that the lungs convey pneuma (oxygen) into the blood [16]. Arteries and veins have common openings in the body and between the ventricles of the heart for proper nourishment. The liver is nourished almost entirely by the heaviest venous blood and the brain by the lightest (porous) blood. A considerable quantity of
blood already elaborated in the veins is taken over through the central muscular part of the IVS and its perforations into the LV and into the arteries. The deep pits in the IVS of the heart are formed for the purpose of communication. The organs need different kinds of useful blood to remain viable [12]. William Harvey boiled and dissected hearts. He did not vivisect the LV of the heart. He stated that all fibres in the septum of a boiled heart are circular as in a sphincter. He demonstrated from the structure of the heart and by observing beating hearts that blood passes from the RV through the lungs into the LV. Harvey ligated the pulmonary artery and fastened a small tube through the vena cava into the RV of the human heart. He forced warm water at considerable pressure into the RV but not a drop of water or blood escaped through the gap into the LV of the heart. Using the same method he demonstrated that water passes from the pulmonary artery through the lungs into the LV of the heart [8]. Harvey published “De Motu Cordis” in 1628. His views on blood circulation became generally accepted within 30 years. Harvey wondered why Galen failed to grasp the correct idea of the circulation [11].

The present author noticed a flow from right to left through the IVS of the heart. Cardiologists claimed this was an artefact of the ultrasound imaging system. Galen presumably vivisected the still living LV of the heart and saw that blood was taken over through the IVS. In the present study an aqueous solution of a black dye was squeezed gently with the fingers through the pulmonary artery into the closed RV and, consistent with Galen’s observations, the author saw dye seeping through the homogeneous central muscular part of the IVS right to left. This communication was preliminarily identified by dissecting fresh pig hearts. The author also dissected the IVS of the pig hearts after boiling and identified the communication completely.

MATERIALS AND METHODS

Fourty pig hearts were regular pig hearts destined for the food industry. All the pigs were aged 6 months and weighed about 50 kg to 55 kg. The sex was unknown and not selected. The pigs were anaesthetised using 80% to 85% carbon dioxide inhalation and a blade was inserted into the common carotid artery. The pigs were relaxed and blood pressure was normal at the time of slaughter. The hearts had no anatomical malformations (Personal communication by Irmeli Sippola [a VET] working for the Government of Finland at the Atria Company that complies with the laws of Finland and directives of European Union). The author employed 2 methods, designated A and B.

Method A

The vena cava and the right atrioventricular orifice of 20 porcine hearts were ligated. The LV wall left to the anterior interventricular sulcus and apical to the coronary sulcus was incised. The wall of the LV was deflected to the left. A plastic bottle containing an aqueous solution of black dye was squeezed gently and repeatedly with the fingers through the pulmonary artery into the RV, thus mimicking the right atrial cycle. The IVS was inspected visually to observe whether any of the black solution was seeping through. Next, the RV was dissected in the same manner as the LV. The inside corner between the septum and the right anterior ventricular wall was dissected in order to inspect the deep pits under the anterior interventricular sulcus. The septum between the deep pits and the central muscular part of the IVS was dissected in order to find the communication and any black dye between the deep pit and the left central muscular part of the IVS. The author suspected that dye may flow into the tissue of the heart through the coronary veins. Ten porcine hearts had the coronary veins patent and 10 porcine hearts also had the coronary veins ligated near the coronary sinus. Time between the slaughter and the experiment was 2–7 days. Twenty warm hearts in a plastic bag were cooled in a refrigerator. The hearts stopped beating at the systole and relaxed again after 2 days.

Method B

The walls of both ventricles of the other 20 pig hearts were removed. The IVS of the pig hearts was kept in boiling water for 2 h. The left endocardium was removed (Fig. 1). The septum was incised anterior to posterior through 2 openings of the communication in the middle of the left muscular part of the IVS (Fig. 2). The layers of the fibres of the muscle were carefully removed as far as the outer layer of the left muscular part of the IVS and the communication anterior to the openings of the communication were visible (Figs. 3, 4).
RESULTS

General description

Method A. The deep pit had a large communication with the RV. The communication had an opening in the deep pit towards the central muscular part of the interventricular septum.
the IVS. The endocardium in the middle of the left muscular part of the IVS of 13 hearts was bloodstained. The same area became black when dye was squeezed through the pulmonary artery into the RV of all 20 hearts. A small amount of dye seeped into the LV of 18 hearts (Fig. 5).

Method B. The communication with the sphincter was visible right to left between the fibres of the muscular part of the IVS on dissection of the other 20 pig hearts after boiling (Fig. 3). The term ‘septal vessel’ (kuuselian vessel) referred to the communication between the fibres of the muscle right to left through the muscular part of the IVS of the heart.

Description in detail

Method A. There was a deep pit 4.5 cm caudally to the aortic valve and 2 cm to the left central muscular part of the IVS through the right IVS formed from the medial wall of the expanding foetal RV communicating to the RV. The deep pit had an opening of the septal vessel (kuuselian vessel) 1 mm or less in diameter between the right and left muscular part of the IVS. In 19 of the 20 hearts the septal vessel (kuuselian vessel) was visible between the fibres of the muscle most commonly located 1 cm (5–20 mm) towards the black central muscular part of the IVS (Figs. 5–8). A small amount of black dye was present...
The IVS of 7 hearts was not bloodstained under the endocardium, because the blood ran off the communication completely as these 7 hearts stopped beating at the systole. The black dye stained the same area in all 20 hearts. The area stained varied from $5 \times 5$ mm to $6 \times 3$ cm. The most common size was $2 \times 2$ cm. A small amount of black dye seeped through the endocardium into the LV in a total of 9 septa of both groups.

The dye made irregular lines towards the endocardium between the fibres of the muscle through the left central muscular part of the IVS formed from the expanding medial wall of the foetal LV. The homogeneous left central muscular part of the IVS had no canals and the dye stained the fibres of the muscle through the septum. The stripe filled with tightly packed black dye was under the endocardium like the endocardial-lined channels presented by Ben-Shachar et al. [4]. The black dye also stained the route through the endocardium slightly black (Figs. 5, 9).

Twenty-three drops of the black dye seeped through the first 10 septa and 15 drops through the last and older 10 septa. No black dye seeped through the last and oldest left endocardium of the septum for about a week in both groups. The communication through the endocardium lost patency as the hearts became older, probably due to necrosis or degeneration, which did not produce artificial channels through the tissue. Muscular autolysis made no artificial channels (Tables 1, 2).

The coronary veins of 10 hearts in group 1 were patent (Table 1), while the coronary veins of 10 he-

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**Table 1.** Hearts 1–10 had the coronary veins patent: the presence and size of the bloodstained area (A, mm) and the dye-stained area (B, cm) in the middle of the left muscular part of the left ventricle is shown; the number of points with drops of black dye seeping through the muscular part of the ventricular septum is shown (C); the communication (septal vessel) length is shown (D, cm); dye staining inside the former (E + or –); the posterior papillary muscle was black (F + or –); the posterior wall of the left ventricle had the black area 1.5 cm, + or – (G).

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arts in group 2 were ligated (Table 2). Four of the hearts in group 1 exhibited black staining of the posterior endocardium of the LV close to the right atrium and the sinus coronarius, most common 10 × 15 mm in size, whereas none of 10 hearts in group 2 showed any staining. The posterior papillary muscle showed some black staining in 6 hearts in group 1 and in 1 heart in group 2. One coronary vein ligation in group 2 might not have been complete. The other results were similar for both groups. The right muscular part of the IVSs did not exhibit black staining. Black dye was not forced through the small RV veins (Thebesian vessels) (Fig. 2) and it did not reach the central muscular part of the IVS through the coronary veins.

Method B. The interventricular septa of 20 pig hearts were dissected after boiling in water for 2 h (Table 3). Boiling caused the IVS to shrink. The fibres of the muscle of the septal vessel (kuuselian vessel) opposite to each other dissociated as the surrounding tissue shrank. The tissue also lost fat as a result of boiling. The RV had an opening into the septal vessel (kuuselian vessel) through the deep pit under the anterior interventricular sulcus in the middle of the IVS. The septal vessel (kuuselian vessel) reached the left central muscular part of the IVS between the muscular fibres (Figs. 3, 4). The fibres of the muscle surrounding the septal vessel (kuuselian vessel) extended over the anterior wall of the LV. The fibres of the muscle surrounding the septal vessel (kuuselian vessel) had 90 degrees grossing of the band of the muscle at the outer layer of the left central muscular part of the IVS by a 1 cm wide band of insertions (Fig. 2). The outer left central muscular part of the IVS was formed from the dense laminar trajectory that was the sphincter of the septal vessel (kuuselian vessel). The septal vessel (kuuselian vessel) had an angle of more than 90 degrees through the sphincter into the LV. Under the endocardium of the left central muscular part of the IVS the septal vessel (kuuselian vessel) had 2 or 3 oval 2 × 5 mm openings. The depth of the openings was half of the left central muscular part of the IVS (Figs. 1–4).

Table 2. Hearts 11–20 had the coronary veins ligated: the presence and size of the bloodstained area (A, mm) and the dye-stained area (B, cm) in the middle of the left muscular part of the ventricle is shown; the number of points with drops of black dye seeping through the muscular part of the ventricular septum is shown (C); the communication (septal vessel) length is shown (D, cm); dye staining inside the former (E + or –); the posterior papillary muscle was black (F + or –); the posterior wall of the left ventricle had the black area 1.5 cm (G + or –).

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The interventricular septa of hearts 1–20 were kept in boiling water for 2 h: the number of openings of the communication (septal vessel) in the middle of the muscular part of the interventricular septum is shown (A); the number of 0.5–3 mm wide and 5–17 mm long communication is shown (septal vessel) (B); the number of openings between the right ventricle and the communication is shown (septal vessel) (C); the communication (septal vessel) right to the sphincter pointed to mild functional activity by dilatation and tone of dark colour (D).

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The sphincter in the middle of the septum was formed from the fibres of the anterior wall of the LV. The fibres of the LV between the aortic base and the middle of the anterior interventricular sulcus extended to the middle of the left muscular part of the IVS and became subendocardial, forming the laminar trajectory and the sphincter in the middle of the left muscular part of the IVS (Figs. 3, 4). The sphincter communicated with the apical and helical muscular trajectory close to the apex (Fig. 1).

**DISCUSSION**

The septal vessel (kuuselian vessel) was surrounded by the sphincter in the middle of the left muscular part of the IVS in agreement with William Harvey. He stated that all the fibres in the septum of a boiled heart are circular as in a sphincter [8]. Activation of the middle third of the septum occurs 5 ms before that of the postero-inferior and antero-superior regions [14]. The septal fascicle of the left His system closed the sphincter as the systole of the LV was beginning. The left to right communication did not result as the earliest LV activation closed the sphincter of the septal vessel (kuuselian vessel) at the very early systole. Venous bifurcation area of the central muscular part of the IVS was also concordant with the sphincter of the septal vessel (kuuselian vessel) [1]. The results were also concordant with a single muscular VSD of the left central muscular part of the IVS, with numerous sieve-like perforations through the right muscular part of the IVS formed from the medial wall of the foetal RV [2]. Agenesis of the sphincter of the septal vessel (kuuselian vessel) in the middle of the left IVS of the heart was the cause of the VSD. The septal vessel (kuuselian vessel) resembled that reported by Galen 1900 years ago [12, 16].

The sphincter of the septal vessel (kuuselian vessel) was feasible to be patent by relaxing and widening the LV at the foetal diastole. These findings were in agreement with Francisco Torrent-Guasp’s model of the helical heart, although he did not report the laminar trajectory to be in the middle of the left muscular part of the IVS [17]. The septal vessel (kuuselian vessel) may have become patent right to left by the diastolic widening of the foetal heart for the diastolic blood pressure, which is higher in the RV than in the LV. Pulmonary venous blood, which represents about 8% of total cardiac output, mixes with oxygenated blood in the left atrium [9]. The sinoatrial node initially activates the right atrium [7]. Oxygenated blood from the umbilical circulation might have reached the outflow tract of the LV and the arteries of the heart and brain through the central muscular part of the IVS. The septal vessel (kuuselian vessel) was the novel structure for the circulation right to left through the muscular part of the IVS of the foetal heart.

Black dye solution seeped right to left through the IVS of all 20 pig hearts. Shrinking of the surrounding tissue by boiling was essential to dissociate the fibres of the muscle around the septal vessel (kuuselian vessel) of the IVS of the other 20 pig hearts. Boiling for 1 h was not enough. The author inspected the septal vessel (kuuselian vessel) of the fresh hearts and after boiling in water for 2 h. In both groups the septal...
vessel (kuuselian vessel) was surrounded by fibres of the muscle. Boiling did not change the appearance of the septal vessel (kuuselian vessel). The septal vessel (kuuselian vessel) was not a canal or channel or blood vessel, but a slit between the fibres of the muscle. The septal vessel (kuuselian vessel) was feasible to appear at the diastole and close tight at the systole.

Black dye seeped through the first 10 septa more abundantly than through the last and older 10 septa. The author conducted experiments on 3 fresh, still warm hearts at the Butcher’s Broom. However, the hearts stopped beating at the systole. No black dye penetrated into the IVS, although a drop of bloody fluid seeped out of the homogeneous left central muscular part of the IVS of all 3 hearts, in agreement with 13 bloodstained areas presented by the results. The results suggest that black dye and blood ran off the communication. For the photographs, the hearts were cooled by –16°C. The hearts had not relaxed after 2 days in the refrigerator. They were relaxed by passing lukewarm water into and out of the RV from a plastic bottle. Forcing water at high pressure from the bottle also closed the septal vessel (kuuselian vessel) and ruined the method.

The pathophysiological question that remained to be answered was: Was it possible to image by angiography the small amount of poorly oxygenated blood flowing through the central muscular part of the IVS from the RV into the LV of the adult heart due to disease and generate the fourth heart sound at the right atrial filling phase? Hypoxia promotes atherosclerosis of heart and brain arteries, heart insufficiency and senile dementia.

The end-diastolic relaxation and widening of the foetal heart at the right atrial filling phase is a fascinating phenomenon, but what was its function? The results suggested that we do not yet fully understand the anatomy, function and embryology of the porcine, African monkey and human heart.

ACKNOWLEDGEMENTS

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The author bought the hearts from the butcher’s of Atria Company in Finland. Atria Company complies with the laws of Finland and the directives of European Union.

REFERENCES