DISTRIBUTION OF POTASSIUM AND SODIUM IN THE HEART OF VARIOUS ANIMALS

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Ionic mechanisms take part in the important physiological functions of the conduction of excitation and muscular contraction. They are also known to be concerned in the pathogenesis of certain diseases. In the present paper we describe a study of the concentration of potassium and sodium in the various parts and tissues of the heart.

EXPERIMENTAL METHOD

We investigated the hearts of 25 frogs (R. temporaria), 40 albino rats, 26 rabbits, 3 cats, 2 dogs, and 18 oxen, i.e., a total of 114 hearts.

Weighed samples for determination of the potassium and sodium were taken from the heart as soon as it was excised and was still beating, or alternatively from hearts fixed in liquid air immediately after extraction from the body. Weighed samples of ox hearts were taken roughly 1-1½ h after the animal had been slaughtered in the abbatoir.

The potassium and sodium concentrations were determined in the myocardium of both atria, in the muscle of the right and left ventricles, and in the interventricular septum. Furthermore, in the ox hearts (in which the conducting system is clearly visible), the concentration of potassium and sodium was determined in the sinoauricular node and along the course of the atrioventricular conducting system: in the atrioventricular node itself, in the common trunk of the bundle of His, and separately in its right and left branches.

Potassium and sodium were determined by flame photometry. The tissue samples were first mineralized with concentrated nitric acid and transferred quantitatively to measuring flasks.

EXPERIMENTAL RESULTS

The mean values of the potassium and sodium concentrations in the various parts of the frogs' hearts are shown in Table 1, the rats', cats', rabbits', and dogs' hearts in Table 2, and the ox hearts in Table 3.

TABLE 1. Total Potassium and Sodium Concentrations in the Myocardium of Various Parts of Frogs' Hearts (R. temporaria)

Part of the heart	Potassium concentration (in meq/kg fresh tissue)		Sodium concentration (in meq/kg fresh tissue)		K + Na	Ratio K/Na
	mean	σ	mean	σ		
Sinus venosus	35.4	±5.0	54.4	±7.4	89.8 ± 12.4	0.65
Atrium	43.8	±6.9	51.0	±8.9	94.8 ± 15.8	0.87
Ventricle	68.0	±6.8	30.4	±5.3	98.4 ± 12.1	2.2

Definite relationships were found in the electrolyte concentrations in the various parts of the heart. For instance, in all the animals the myocardium of the atria contained less potassium and more sodium than the myocardium of the ventricles.

It was also discovered that the right atrium, like the right ventricle, was less rich in potassium than the left atrium and the left ventricle, and conversely, that the latter contained less sodium than the former. The interventricular septum possessed the same concentrations of potassium and sodium as the left ventricle. The lowest potassium and highest sodium concentrations in the frog's heart were found in the sinus venosus, and the converse was true of the ventricle. The atria occupied an intermediate position.

TABLE 2. Total Potassium and Sodium Concentrations in the Myocardium of Various Parts of Rats', Cats', Rabbits', and Dogs' Hearts

Object	Parts of the heart	Potassium concentration (in meq/kg fresh tissue)		Sodium concentration (in meq/kg fresh tissue)		Total concentration of potassium and sodium (meq)	Ratio K/Na
		mean	σ	mean	σ		
Rats	Atrium	61.5	±9.6	64.2	±10.4	125.7 ± 20	0.97
	Right ventricle	79.1	±5.0	44.3	±7.0	123.4 ± 12	1.8
	Left ventricle	81.2	±5.1	41.6	±7.2	122.8 ± 12.3	1.96
Cats	Right atrium	59.7	±6.1	52.0	±4.5	111.7 ± 10.6	1.1
	Left atrium	62.3	±5.4	50.0	±5.2	112.3 ± 11.6	1.2
	Right ventricle	77.0	±2.6	39.2	±3.0	116.2 ± 5.6	1.97
	Left ventricle	78.3	±2.1	39.0	±4.6	117.3 ± 6.7	2.0
Rabbits	Right atrium	58.0	±3.7	59.0	±1.7	117.0 ± 5.4	0.98
	Left atrium	63.7	±2.2	56.1	±2.3	119.8 ± 4.5	1.1
	Right ventricle	70.0	±3.7	45.5	±5.8	115.5 ± 9.5	1.56
	Left ventricle	75.8	±3.4	42.3	±2.4	118.1 ± 5.8	1.8
	Interventricular septum	75.8	±3.5	42.1	±2.5	117.9 ± 6	1.8
Dogs	Right auricle	69.0		46.0		115	1.5
	Left auricle	72.0		43.0		115	1.67
	Right ventricle	85.0		30.0		115	2.83
	Left ventricle	87.0		29.0		116	3.0

Similar relationships between potassium and sodium in the myocardium of the various parts of the heart have also been found in researches conducted on the tortoise [11], rabbit, and dog [2, 9], and ox [1, 10], and also in investigations of the electrolyte composition of the human heart [3, 5].

In our experiments we found that the myocardium of the atria and ventricles possessed equal total concentrations of potassium and sodium (see Tables 1-3). Hence, despite differences in the potassium and sodium concentrations in each part of the heart, the total of these elements was the same. The only exception to this rule was the ox heart, the atria of which had a slightly greater total concentration of potassium and sodium than the ventricles.

Another noteworthy feature was the closely similar total concentrations of potassium and sodium in the myocardium of the atria and ventricles of the various warm-blooded animals. Here again, the exception was the ox heart, in which the sum of potassium and sodium was slightly higher than in other warm-blooded animals.

During the analysis of the findings indicating the heterogeneous electrolyte composition of the myocardium of the atria and ventricles, the question arises whether this heterogeneity is a feature of the myocardium itself or whether it is the result of accessory factors. The latter must include differences in the water content of the myocardium of the atria and ventricles, differences in their content of connective tissue, and differences in the extent of the extracellular space.

In order to exclude the effect of different concentrations of water in the atria and ventricles on the absolute values of the potassium and sodium concentrations in the heart tissues, we introduced the ratio K/Na. This is determined by the ratio between the absolute or percentage content of potassium and sodium in the tissues, and is not dependent on the presence of other components (when the ratio is calculated, these components cancel each other).

The ratio K/Na for the myocardium of the atria was found to be approximately 1, and for the myocardium of the ventricles 2. Only in the dogs was this ratio rather higher in both the atria and ventricles. Hence, using the different values of the K/Na ratio for the atria and ventricles as a basis for discussion, it may be assumed that the heterogeneity of the electrolyte composition of these tissues has nothing to do with differences in the water content.

However, the introduction of the ratio K/Na did not exclude the effect on the potassium and sodium levels in the atria and ventricles of those tissue components which also contain these ions. These elements include the connective tissue and the tissue lymph contained in the extracellular space.

TABLE 3. Total Potassium and Sodium Concentrations in the Tissues of Various Parts of the Ox Heart

Tissue and part of the heart	Potassium concentration (in meq/kg fresh tissue)		Sodium concentration (in meq/kg fresh tissue)		K + Na	Ratio K/Na
	mean	σ	mean	σ		
Myocardium of right atrium	55.9	±6.1	85.1	±6.9	141.0 ± 13	0.66
Myocardium of right auricle	55.6	±6.7	85.4	±9.8	141.0 ± 16.5	0.65
Myocardium of left atrium	68.4	±5.0	70.8	±8.0	139.2 ± 13	0.97
Myocardium of left auricle	67.8	±5.2	69.0	±5.5	136.8 ± 11.7	0.98
Myocardium of right ventricle	79.3	±1.9	49.0	±4.7	128.3 ± 6.5	1.6
Myocardium of left ventricle	81.8	±1.8	43.1	±2.7	124.9 ± 4.5	1.9
Myocardium of interventricular septum	81.7	±1.8	43.2	±2.7	124.9 ± 4.5	1.9
Sinoauricular node	49.7	±3.9	120.0	±9.6	169.7 ± 13.5	0.41
Atrioventricular node	48.3	±4.5	123.0	±12.0	171.3 ± 16.5	0.39
Common trunk of bundle of His	53.0	±6.0	90.0	±8.1	143.0 ± 14.1	0.59
Right branch of bundle of His	64.8	±4.5	83.0	±7.1	147.8 ± 11.6	0.78
Left branch of bundle of His	65.0	±5.3	82.0	±9.6	147.0 ± 14.9	0.79
Chordae tendineae	32.7	±6.4	89.8	±6.0	123.5 ± 12.4	0.36

It has been shown histologically that the atria are richer in connective tissue than the ventricles. Connective tissue, as is shown by information in the literature [4] and our own results (see Table 3, chordae tendineae), is characterized by a high sodium and a low potassium concentration. The difference between the potassium and sodium concentrations in the atria and ventricles may therefore appear, at first glance, to be due to their different content of connective tissue. However, it would be difficult to understand from this point of view the difference between the concentrations of potassium and sodium in the right and left atria, in which the connective tissue content is relatively equal, and also between their concentrations in the two ventricles.

To some extent the difference between the potassium and sodium concentrations in the atria and ventricles may be explained by differences in their extracellular space. For instance, according to some writers [1], the extracellular space of the atria in rats and rabbits, determined by the inulin and sugar method, is actually rather larger than that of the ventricles. However, this difference is not large enough to account for the whole of the variation between the potassium and sodium concentrations in these parts of the heart.

It is more probable, therefore, that the distribution of potassium and sodium in the myocardium of the atria and ventricles, disclosed by our experiments, characterizes some specific feature of these tissues, and is not the result of the operation of accessory factors.

The total concentration of potassium and sodium was also studied in the specific tissue of the atrioventricular system and in the sinoatrial node. These investigations were conducted on ox hearts, in which the conducting system is readily distinguishable and relatively large. It is clear from Table 3 that the sinoatrial and atrioventricular nodes contained potassium and sodium in almost the same relative proportions. Their potassium concentration was smaller than in all the remaining tissues of the heart. Meanwhile, these structures possessed a higher sodium concentration than any other tissue of the heart. Their K/Na ratio was among the lowest—about 0.4; only the chordae tendineae possessed a lower ratio than this, namely 0.36, and these consist almost entirely of connective tissue.

The total concentration of potassium and sodium in the sinoatrial and atrioventricular nodes was higher than in the other tissues of the heart. This resulted from their very high sodium level. Similar results are cited by other writers [4, 6].

This distribution of potassium and sodium in the node tissue was evidently a specific feature and not dependent on the presence of connective-tissue and nerve elements. Davies and co-workers, who determined the number of nerve elements in the bundle of His (3%) and calculated the possible distortion of the electrolyte composition of the conducting system on account of the fibrous tissue, concluded that these two components cannot significantly affect the potassium and sodium concentrations in the specific musculature [4].

Determination of the electrolytes along the course of the atrioventricular system revealed an interesting fact. In the common trunk of the bundle of His the potassium and sodium concentrations differed slightly from those in the atrioventricular node. The common trunk of the bundle of His, as a rule, contained more potassium and less sodium than the atrioventricular node; its ratio K/Na was 0.59. An even higher potassium and lower sodium level was found in the right and left branches of the bundle of His; their K/Na ratios were 0.78 and 0.79, respectively.

The total potassium and sodium concentration in the trunk of the bundle of His and its branches remained higher than in the myocardium of the various parts of the heart, although it fell below that in the sinoatrial and atrioventricular nodes.

Our results indicating the distribution of potassium and sodium in the specific muscle tissue thus showed a difference between its electrolyte composition and that of the contractile muscular elements in the various parts of the heart. It is natural to associate this difference with the difference in the physiological functions performed by these tissues. Characteristically the myocardium, in whatever part of the heart, has a high potassium and a low sodium concentration. The potassium concentration, moreover, is directly dependent on the muscular effort exerted by the particular part.

Meanwhile, the tissues performing an automatic function and conducting excitation possess the highest sodium and lowest potassium concentrations. The sodium level falls gradually from the region of the sinoatrial and atrioventricular nodes to the branches of the bundle of His, parallel to the rise in their potassium concentration. It may be suggested that the high sodium concentration of the sinoatrial and atrioventricular nodes is associated with the generation of automatic rhythmic activity. Parallel to the fall in the sodium level in the conducting system, the ability of the specific muscle to carry out its automatic function also falls. The same thought has been expressed by other writers, who assert that the automatic function possessed by different parts of the heart is directly proportional to their sodium concentration and inversely proportional to their potassium concentration [8].

SUMMARY

The total potassium and sodium content was studied in various portions and tissues of the heart of 25 frogs, 40 rats, 26 rabbits, 3 cats, 2 dogs and 18 oxen. The myocardium of different portions of the heart may be placed in the following order according to the rise of the potassium content: the right and left auricle, the right and left ventricle. The sodium content in these portions decreases in reverse order to the potassium. Level K/Na coefficient for auricular myocardium approaches 1, and for ventricular myocardium, 2. In specific muscles of the ox heart the content of potassium is lower than in the myocardium and increases from the sinus and atriventricular nodes to the bundle of His and the fasciculi of the bundle of His. The sodium content therein has a reverse distribution gradient. Their K/Na coefficients are correspondingly 0.4, 0.6 and 0.8. The sum of potassium and sodium content in the myocardium of auricles and ventricles is the same. The sinus and atrioventricular nodes are characterized by the highest sum of potassium and sodium level as compared with other portions of the conduction system and myocardium.

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