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THE BLOOD FLOW IN SKIN AND MUSCLE OF THE HUMAN FOREARM

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The venous occlusion plethysmograph measures the total blood flow through all component tissues of a limb segment. It does not give any indication of the relative flow through the skin, muscle and supporting tissues. In the past, observed changes in forearm blood flow have been ascribed, by different workers, to changes in the different component tissues of the limb segment. However, no direct quantitative measurements of the flow in these different tissues have been made in man. Estimates of skin blood flow have been made by Hertzman (1948), using the photo-electric plethysmograph. Behnke & Willmon (1941) have used the rate of absorption of helium through the skin as an indication of cutaneous blood flow. Hardy & Soderstrom (1938) have, by a study of the skin and deep temperatures, attempted to assess the skin blood flow. The heat elimination of the skin has been measured by Hensel (1952) using a modification of Aschoff's (1944) continuous-flow calorimeter. All these methods can be considered to give an indication of changes in the skin blood flow, but none of them has been correlated with a method which gives a quantitative record of the cutaneous blood flow. The method of physiological skinning of the forearm by iontophoresis with adrenaline developed by Barcroft, Bonnar, Edholm & Effron (1943) has been used to measure skin flow. The forearm blood flow may vary considerably from day to day, even with the subject at rest. Making use of these fluctuations in forearm blood flow, induced by internal and environmental factors, it is possible to estimate the skin and muscle blood flows occurring in the forearm over a substantial range of flows in that segment, and the results are presented in this paper (Cooper, Edholm & Mottram, 1954).

METHODS

Techniques. Forearm blood flows were measured by means of a water-filled venous occlusion plethysmograph. Records of volume changes were obtained using an electrical volume recorder (Cooper & Kerslake, 1951). The wrist-cuff was inflated to 200 mm Hg pressure for 1 min (Kerslake, 1949). The venous occlusion cuff was then alternately inflated to 70 mm Hg pressure for 5 sec

and opened to atmosphere for 5 sec. This cycle of cuff inflation was maintained during the recordings. A set of twenty inflow traces was obtained in this way over a period of 4 min 20 sec, and then both the wrist-cuff and the collecting cuff were left open to atmosphere for 5 min 40 sec. Further inflow recordings were made in this manner throughout the experiment. The mean slope of the twenty inflow records in each set was used to calculate the mean forearm blood flow during that period of observation.

In order to arrest the skin circulation so that an estimate might be made of both skin and muscle blood flows, adrenaline iontophoresis was carried out in the following manner. The arm was shaved and cleaned with ether prior to the start of the experiment. At the appropriate time the arm was removed from the plethysmograph, and the hand was inserted into a rubber glove which was sealed at the wrist with waterproof adhesive tape. The forearm and hand were placed as far as the elbow into a cylindrical brass pot, the top edge of which was covered with an insulating material to prevent burns occurring from direct contact of the arm with the brass rim. The pot was filled with a solution of adrenaline (free base obtained from Boots Pure Drug Co. Ltd.) at a concentration of 1 : 2000, in 0·05 % (v/v) H_3PO_4 and adjusted to a pH of 4·5 with a phosphate buffer. The solution was prepared within half an hour before use and kept at 34° C. The brass cylinder was connected to the positive pole of a 45 V battery, the negative pole of which was connected in series with variable resistances (500,000 Ω and 5000 Ω), a milliammeter, and an electrode on the leg. The current was gradually increased until the intensity of the tingling was at the limit of the subject's tolerance, or until 20 mA was passing through the circuit. This current strength was maintained constant for 10–20 min, and was then gradually decreased to zero. The arm was removed from the pot, the glove was stripped off, the forearm dried and returned to the plethysmograph in the exact position which it had previously occupied.

Procedure. The subjects for these experiments were healthy adults of both sexes, aged 20–45 years. They lay on a couch in a room, the temperature of which was controlled, usually between 23 and 25° C. Pulse rate, blood pressure and mouth temperature were recorded at 10 min intervals. The arm was placed in a water-filled plethysmograph at about heart level, and the water temperature was maintained at 34° C in most experiments, but occasionally at 30 or 35° C. Five sets of inflow traces were obtained and then the iontophoresis of adrenaline was carried out. The arm was replaced in the plethysmograph and at least five more sets of inflows were recorded. All experiments ended not later than 1 hr after the end of iontophoresis. A rise of pulse rate and blood pressure associated with palpitations and a feeling of apprehension by the subject during or after iontophoresis of adrenaline was taken to indicate the absorption of adrenaline into the systemic circulation.

RESULTS

Evidence that adrenaline iontophoresis arrests the skin circulation. When an experiment ended, the arm was examined for the persistence of blanching during reactive hyperaemia and immersion in hot water. Any reddening in the iontophoresed area was indicative of incomplete arrest of the skin circulation in the segment. An appearance resembling post-mortem lividity was observed in the iontophoresed area, and it was unchanged during a reactive hyperaemia. In most of those experiments in which the iontophoresis was adjudged to be complete, by means of the reactive hyperaemia and hot water tests, the post-iontophoresis arm flows were reduced below the pre-iontophoresis flow level, and they remained steadily at the new value for about 1 hr. This change, together with the absence of flushing during reactive hyperaemia, suggested that the skin blood flow, if not abolished, was greatly reduced. Further evidence was sought on one subject (O.G.E.) by direct observation. Two

experiments were performed in which the forearm was treated with adrenaline in the usual way but the room temperature was raised to produce a high skin blood flow. A rubber cuff was bound round the upper arm and inflated to 200 mm Hg pressure. Two incisions were made in the skin and well into the subcutaneous fat, one in the treated area, and one just above the line of blanching. The cuff which had been inflated for 4 min was deflated. Free bleeding took place from the skin edges of the incision in the untreated skin but not in the iontophoresed area. In both incisions, however, there was a little oozing of blood from the vessels in the subcutaneous fat. These observations confirmed the suggestion that the blanched skin was bloodless, and suggest further that the adrenaline had not passed appreciably into the subcutaneous region.

Evidence that absorption of adrenaline into the general circulation did not affect the blood flow in the forearm muscles is provided by other experiments (Cooper, Edholm, Fletcher, Fox & Macpherson, 1954), in which the blood flow in both forearms was measured simultaneously. During and after a satisfactory iontophoresis of adrenaline into one arm, the blood flow in the other arm remained constant. It has also been suggested that during iontophoresis adrenaline could reach the muscle vessels via vascular channels penetrating from the skin and so increase the muscle blood flow. In the experiments described in this paper, the blood flow has been measured after iontophoresis in order to assess the muscle flow, during the time when the skin circulation is arrested. Under these conditions, such penetrating vascular channels, if they exist, would have no blood flowing through them.

Dissection of the human forearm. Fresh post-mortem material was used, five forearms from five different subjects being dissected. A segment of the forearm was removed, corresponding in position and length to that part of the arm normally enclosed in the plethysmograph. This was weighed and the volume measured by water displacement. A complete dissection was made and the forearm separated into the component tissues, i.e. skin, subcutaneous fat, muscle, fascia, tendon, nerves, blood vessels and bone. The periosteum and interosseous membranes were not separated from the bone. Each tissue was first weighed and then the volume determined by water displacement. The results are shown in Table 1. Under the heading of fat, etc., is grouped subcutaneous fat, fascia, nerves and blood vessels.

Although the initial size of the forearm dissected varied considerably, there is less difference in the proportion of the tissues than was anticipated.

Forearm blood flows before and after adrenaline iontophoresis. A total of thirty-nine experiments was performed. The mean slope of all the inflow traces obtained before adrenaline iontophoresis was calculated and, when converted into ml. blood/100 ml. forearm/min, was taken as the mean forearm blood flow before the adrenaline treatment. It was considered to be the sum of skin and

muscle blood flows, with a small contribution from bone, fat and connective tissues. A similar average post-iontophoresed forearm blood flow was computed. The difference between the pre-iontophoresis and the post-iontophoresis flows was taken to represent the skin blood flow under these conditions. Of the thirty-nine observations, eight were rejected; the values obtained in these experiments, and the reasons for their rejection are shown in Table 2. The remainder of the observations are presented in Table 3. The resting level of blood flow varied from 1·5 to 10·5 ml./100 ml. forearm/min and skin blood flow varied from 0 to 6·0 ml./100 ml. forearm/min. No attempt was made to give

TABLE 1. Dissection of the forearm

Complete segment		Skin			Bone			Tendon			Fat, etc.			Muscle		
(*a*)	(*b*)	(*a*)	(*b*)	(*c*)	(*a*)	(*b*)	(*c*)	(*a*)	(*b*)	(*c*)	(*a*)	(*b*)	(*c*)	(*a*)	(*b*)	(*c*)
388	340	29	30	8·6	82	52	15	25	24	7	26	26·5	7·8	220	220	62
392	354	29	30	8·5	87	53	15	18	17	5	23	23	6·5	235	230	65
400	370	40	39	10·5	78	50	13·5	37·5	36·9	9·8	45	45	12	172	169	54
453	430	40	35	8·5	92	70	15	15	16	3·8	29	29	6·8	282	280	65
675	616	45	44	7·1	89	56	10	32	32	5·2	35	40	6·5	475	460	72
Average				8·6%			13·7%			6·1%			8%			63·6%

In column (*a*) is given the weight of the part in grams; in column (*b*) the volume in ml.; and in column (*c*) the percentage volume. The average values are the average volumes of the different tissues. The heading 'fat, etc.' includes fat, fascia, nerves and blood vessels.

mean values to these quantities, since it would be misleading and imply a constancy which does not exist. The values obtained for muscle blood flow and skin blood flow have been plotted against the total forearm blood flows in Figs. 1 and 2. Regression equations have been calculated for these two sets of points, and the regression line drawn on the figures. The upper part of each line is dotted, there being too few points to justify the assumption of linearity. The equations are:

$$\text{skin flow} = 0{\cdot}53 \times \text{total forearm flow} - 0{\cdot}83,$$

$$\text{muscle flow} = 0{\cdot}47 \times \text{total forearm flow} + 0{\cdot}83.$$

Using the average figures for the volume of skin and muscle obtained from the dissections, the range of skin blood flow was found to be from 0 to 70·5 ml. blood/100 ml. skin/min, and the range of muscle flows from 1·8 to 9·6 ml. blood/100 ml. muscle/min.

General observations. There was marked pilo-erection in the blanched area after iontophoresis of adrenaline, which at times persisted for some hours after the end of the experiment. The pallor persisted in some subjects for as long as 6 hr after treatment. On occasions symptoms, which were probably due to the absorption of adrenaline, occurred several hours after the experiment ended. This suggested that, as a precaution, a trial iontophoresis using a low current strength should be carried out on each subject to exclude those who might have unpleasant symptoms after the usual experiment.

TABLE 2. Forearm blood flows before and after adrenaline iontophoresis. The results of the eight experiments which were rejected

Blood flows ml. blood/100 ml. forearm/min			
Resting	Post-iontophoresis ('Muscle')	Skin	Reason for rejection
3·40	2·90	0·5	Rise in pulse rate and blood pressure
2·80	—	—	Incomplete blanching of forearm
2·70	3·10	−0·4	Pulse rate rose after iontophoresis
—	—	—	Inflow curves unreadable because of respiratory fluctuations
2·40	1·90	0·5	Rising post-iontophoresis flows
2·17	2·27	−0·1	Palpitations and rise in pulse rate after iontophoresis
2·95	2·06	0·89	Continuous rise in post-iontophoresis flows
—	—	—	Inflow curves unreadable because of respiratory movements

TABLE 3. Forearm blood flows before and after adrenaline iontophoresis

	Blood flows					
	Post-iontophoresis					
	Muscle		Skin			
Resting ml. blood/100 ml. forearm/min	(*a*)	(*b*)	(*a*)	(*b*)	Plethysmograph temp. (° C)	Room temp. (° C)
1·45	1·16	1·8	0·29	3·4	30·5	23–24
1·60	1·60	2·5	0	0	30·0	24–25
1·90	1·40	2·2	0·50	5·9	34·0	23–24
2·02	1·64	2·6	0·38	4·4	30·0	23–24
2·05	1·63	2·6	0·42	4·9	30·5	24–25
2·10	1·90	3·0	0·20	2·3	34·0	23–24
2·12*	2·06	3·2	0·06	0·7	34·0	23–24
2·20	2·20	3·5	0	0	34·0	19–20
2·27	1·63	2·6	0·64	7·5	34·0	23–24
2·30	1·60	2·5	0·70	8·2	34·0	22–23
2·39	2·16	3·4	0·23	2·7	34·0	23–24
2·45	1·62	2·6	0·83	9·7	34·0	24–27
2·60	2·15	3·4	0·45	5·3	34·0	24–25
2·61	1·95	3·1	0·66	7·7	34·0	25–26
2·70	2·00	3·1	0·70	8·2	34·0	23–24
2·90	1·80	2·8	1·10	12·9	34·0	22–23
3·03	3·03	4·8	0	0	34·0	23–24
3·18	2·37	3·7	0·81	9·5	34·0	23–24
3·20	2·20	3·5	1·00	11·7	34·0	23–24
3·20	2·70	4·2	0·50	5·9	35·0	25–26
3·60	2·80	4·4	0·80	9·4	34·0	23–24
3·80	2·10	3·2	1·70	20·0	34·0	26–27
4·00	2·60	4·1	1·40	16·4	34·0	24–25
4·30	2·70	4·3	1·60	18·8	34·0	22–23
4·50	3·43	5·4	1·07	12·6	30·5	22–23
5·30	2·80	4·4	2·50	29·4	34·0	25–26
5·60	3·40	5·4	2·20	25·8	34·0	24–25
6·00*	5·95	9·4	0·05	0·6	34·0	25–26
6·17	2·01	3·2	4·16	49·0	34·0	23–24
7·64	6·12	9·6	1·52	15·8	34·0	24–25
10·50	4·50	7·1	6·00	70·5	34·5	23–24

* The differences between these resting flows and their post-iontophoresis flows are within the limits of experimental error:

where '*a*' = muscle or skin blood flow in ml./100 ml. forearm/min;

where '*b*' = muscle or skin blood flow in ml./100 ml. muscle or skin/min.

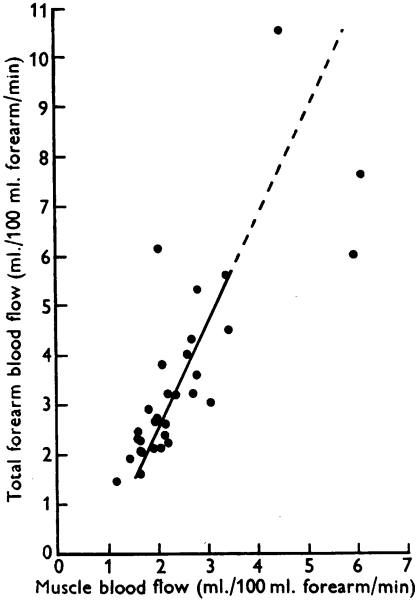

Fig. 1

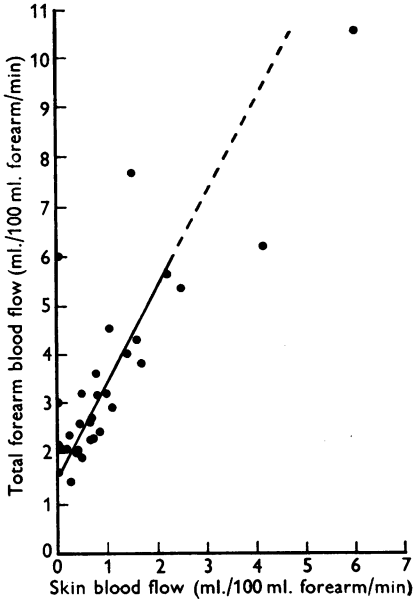

Fig. 2

Fig. 1. Muscle blood flow calculated from adrenaline iontophoresis experiments, plotted against total forearm blood flow. Although the calculated regression line suggests a linear relationship, this may not hold good at the higher rates of flow.

Fig. 2. Skin blood flow, calculated from adrenaline iontophoresis experiments, plotted against total forearm blood flow. At low rates of forearm blood flow, skin blood flow is nil, but increases steeply as total flow rises.

DISCUSSION

The evidence from the experiment in which the forearm was incised strongly suggests that skin blood flow is zero in a blanched limb segment. Any small flow of blood through the skin after iontophoresis would give a slightly high figure for muscle blood flow, and a consequent underestimate of the flow through the skin. This possibility cannot be excluded, since direct observation of incised skin was not made in each experiment. Under the heading of muscle blood flow is included the flow through muscle, tendon, fat, connective and bony tissues. The figures available for the bone blood flow in healthy subjects from the work of Edholm, Howarth & McMichael (1945) give a value of 0·5–1·0 ml. blood/100 ml. bone/min. This would make the muscle flow as estimated here too high by 0·07–0·14 ml. blood/100 ml. forearm/min. Tendon, connective tissue and fat are relatively avascular tissues, and no measurement of the blood flow in them has yet been made. The values obtained for the composition of the forearm agree closely with those of Abramson & Ferris (1940), but differ from

the figures obtained by Grant & Pearson (1938) and by Skelton (1927). Grant & Pearson estimated the composition of the arm by a radiographic technique which was open to inaccuracy in interpretation. If the figure for skin volume given by Skelton is divided by the body surface area, the extraordinary value of 6·5 mm for mean skin thickness is obtained. An explanation for this statement is that the subcutaneous tissue is included in the definition of skin. While variation in the amounts of each tissue in the forearm would make some difference to the values obtained for the skin and muscle flows, it is not great enough to influence their order of magnitude.

It is clear from an inspection of Figs. 1 and 2 that the higher the total forearm blood flow the higher are both the skin and muscle components. Regression equations have been calculated from the observations, and there is some scatter of individual results. An estimate can be made of skin or muscle blood flows from recorded total forearm flows which do not exceed a value of 5·6 ml./100 ml. forearm/min, the greatest error involved in such an estimate being 36%. At higher flows, the variation is too great for the computation of skin or muscle flows. Different treatments (plethysmograph and room temperatures) were used in some experiments, and it was felt that the calculation of correlation coefficients from the observations might give spurious values.

In some early experiments it appeared that forearm blood flow after treatment was steadier than that recorded before treatment, indicating that the muscle vascular system was less subject to rapid fluctuation than that of the skin. Coefficients of variation were calculated from the observations and it was found that there was no significant difference in variability of blood flow before and after adequate iontophoresis. Fig. 3 shows blood flow tracings obtained simultaneously from an experiment in which the treated (left) and untreated (right) forearms were investigated. It can be seen that the same pattern of variation of blood flow occurs in the treated as in the untreated arm.

The total cutaneous blood flow has been estimated by Hardy & Soderstrom (1938) using temperature measurements. At an environmental temperature of 35° C, in a nude subject at rest, the skin blood flow was estimated to be 278 ml./m^2 body surface/min. The value obtained by Behnke & Willmon (1941) under similar conditions was 230 ml./m^2 body surface/min. These figures can be applied to the forearm, and the skin blood flow in that segment so calculated was 1·5 and 1·2 ml. blood/100 ml. forearm/min respectively. These estimated forearm skin blood flows are well within the range obtained in the present work. The results obtained with the photo-electric plethysmograph cannot be compared with other values since this instrument gives essentially qualitative readings.

The adrenaline iontophoresis method makes it possible to correlate skin blood flow with total forearm blood flow. It is clear that averages obtained on any one occasion have little value in relation to the actual flows under different

environmental conditions. Skin flow is, however, related to total flow under the conditions described here. It would be wrong to conclude that, at any given total forearm flow, there is a fixed ratio between skin and muscle blood

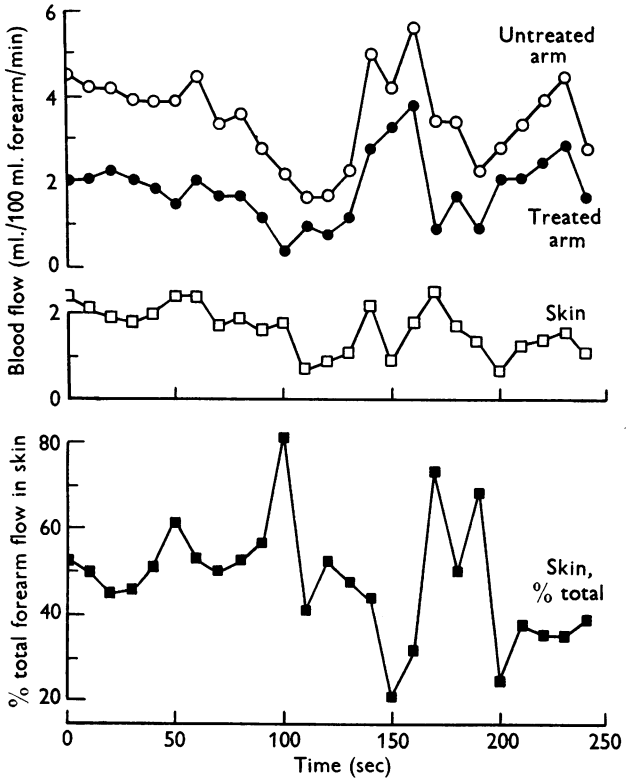

Fig. 3. Individual forearm blood flows recorded simultaneously in the two arms, in one of which the skin circulation was suppressed (phoresed). The difference between the two flows is plotted as the skin blood flow. In the lower part of the figure the skin blood flow is plotted as a percentage of the total forearm flow. It will be seen that the variability in blood flow in the intact arm is reflected in the 'skinned' arm, i.e. muscle blood flow is not more constant than skin blood flow. ○—○, untreated forearm; □—□, skin blood flow; ●—●, treated, i.e. adrenaline/iontophoresed forearm; ■—■, skin blood flow as percentage of total arm flow.

flow. A plot of skin blood flow against muscle blood flow in Fig. 4 shows that there is considerable variability in the relationship between these quantities (see Table 4). There are conditions under which the skin blood flow can decrease and the muscle flow increase, for example when adrenaline is given intravenously. So it is only in resting states, as described in this study, that approximate predictions can be made of skin or muscle blood flows from the total forearm blood flow.

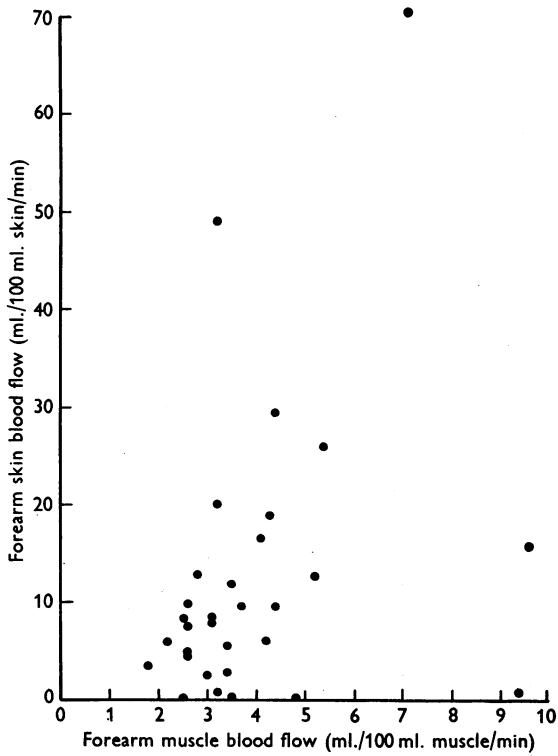

Fig. 4. Skin blood flow, plotted against muscle blood flow. There is a considerable spread showing that the relationship is not fixed.

TABLE 4. Average partition of forearm blood flow

Total ml./100 ml. forearm	Muscle flow percentage and range	Skin flow percentage and range
Up to 3	81 62–100	19 0–38
3–6	72·5 53–100	27·5 0–47
6 and over	50·5 32·5–80	49·5 20–67·5

SUMMARY

1. Forearm blood flows were measured, at a room temperature of 23–25° C before and after iontophoresis of adrenaline into the skin of the arm.

2. Evidence is presented suggesting that the skin blood flow is effectively stopped by the adrenaline iontophoresis.

3. Over a range of forearm blood flow from 1·45 to 10·5 ml./100 ml. forearm/min, in thirty-one experiments, the muscle blood flow was found to vary

between 1·8 and 9·6 ml. blood/100 ml. muscle/min, and the skin blood flow between 0 and 70·5 ml./100 ml. skin/min. The muscle blood flows and the skin blood flows have been plotted against the resting forearm flows, the relationship being shown.

4. The errors in the technique, the comparison of these results with those of other workers, and the possibility of predicting skin and muscle flows from the total forearm blood flows are discussed.

We are grateful to colleagues and students who acted as subjects in this investigation.

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