27. THE DETERMINATION OF THE VISCOSITY OF HUMAN MILKS AND THE PRENATAL SECRETIONS

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THAT the marked variations which are known to exist in the viscous properties of human mammary secretions are of interest in studying both normal and pathological conditions has been pointed out by Waller [Waller *et al.* 1941]. In order to assist in a further investigation of the question it seemed advisable to devise a viscosimeter suitable for the study of such materials and to establish the general character of their rheological properties.

In the case of prenatal secretions removed from the breast by manipulation, it is frequently the case that only about a millilitre of material is available for the viscosity measurement, nor is the viscosity always a constant independent of shearing stress. A viscosimeter must therefore be designed which will give a series of readings on a very small sample at a number of different shearing stresses. The instrument shown in Fig. 1 is in principle quite similar to several others already described in the literature, especially by Ostwald and his coworkers, but is designed as the most suitable modification for the present purpose.

The apparatus consists of a glass capillary tube (*A*) sealed into two wider tubes but at right angles so that the whole can be immersed in a thermostat water bath. Approximately 1 ml. of the material to be tested is run by means of a pipette into the wide mouth *B* and allowed to stand for a few moments to reach temperature equilibrium and to find its level on the two sides of the viscosimeter. If there is much 'creaming' this must be done as quickly as possible, the milk being brought approximately to temperature previously in another vessel. A temperature of 37° is used, partly because this is the natural temperature for such materials and partly because it has been shown in the case of cow's milk (especially cream) by Scott Blair *et al.* [1939] that additional rheological complications are introduced when temperatures are used at which the fat phase is liable to solidify.

The sliding scale (*C*) is then adjusted so that the zero of the scale corresponds to the meniscus of the sample.

The sample is then blown into the tube by means of a rubber tube attached to the other arm. When the pressure is released, the column of liquid starts to

Fig. 1.

fall along the scale (C). When the meniscus passes a convenient point on the scale (h_1) (18 cm. is usually suitable) a stop-watch is started and the time taken for the meniscus to fall to half this height (h_2) is recorded (t_1). The test is then repeated starting at h_2 and timing the fall to h_3 , a distance half that of h_2 , i.e. a quarter of the original h_1 . This second time t_2 should be equal to t_1 if the material is a true fluid obeying Poiseuille's law. If the material is not a true fluid, the ratio of t_1 to t_2 is an index of the extent of the anomaly. The viscosity in c.g.s. units (poises, or better, the kinematic viscosity of which the unit is the stokes, and which is equal to the viscosity/density) is best derived by standardizing the instrument by means of sucrose solutions of known viscosity, and a number of instruments having capillaries of different radii should be used conveniently to cover the whole range of human mammary secretions. A constant is thus obtained for each instrument from which viscosities can be worked out in c.g.s. units (poises, or stokes) by multiplying by the value of t_1 . Where the viscosities differ for the two ranges of stress, that calculated from a , fall from $h_1=18.0$ to $h_2=9.0$ is arbitrarily chosen. The errors involved in this choice of stress are small compared with the range of viscosities involved. This simple test takes only a few moments to complete, and the result is calculated by means of a single multiplication.

The above treatment is derived from the following considerations, which also serve to give an absolute standardization of the instrument if such is desired. For materials differing appreciably from truly fluid behaviour, or where only very small samples are available, the direct application of the equation now to be derived is necessary.

Let V be flow rate of sample through capillary in $\text{cm.}^3/\text{sec.}$,

R_c be radius of capillary (cm.),

P be pressure produced by head h at time t sec., in dynes/ cm.^2 ,

L be length of capillary tube (cm.),

η be viscosity and ρ the density of sample,

R_w be radius of wide tube (cm.) (assumed large compared with R_c),

v be velocity of meniscus falling in wide tube (cm./sec.).

From Poiseuille's law we have

$$V = \frac{P\pi R_c^4}{8L\eta}$$

(assuming that the viscous resistance in the wide tube is negligible),

$$\text{or } v = \frac{PR_c^3}{8L\eta} \times \frac{R_c^2}{R_w^3} = \frac{PR_c^4}{8L\eta R_w^3}.$$

The rate of decrease of head is twice this, since the meniscus falls on one side but rises at an equal rate on the other; hence

$$\frac{dh}{dt} = -\frac{h\rho g R_c^4}{4L\eta R_w^3},$$

where g is the gravity acceleration,

$$\text{or } t = -\frac{4L\eta R_w^3}{\rho g R_c^4} \int \frac{1}{h} dh = -\frac{4L\eta R_w^3}{\rho g R_c^4} \log_e h + C,$$

where C is an integration constant.

Now, when $t=0$, we have $h=h_0$, hence

$$C = \frac{4L\eta R_w^3}{\rho g R_c^4} \log_e h_0;$$

hence η/ρ , the kinematic viscosity, which we will write ν , is given by

$$\eta/\rho = \nu = \frac{t}{\log_{10}(h_0/h)} \frac{g R_c^4}{4L R_w^3} 0.4343.$$

Thus, if we are prepared to discount differences in the densities of the samples, i.e. to use kinematic rather than dynamic viscosities, we see that the slope of the curve plotting t against $\log_{10} (h_0/h)$ has only to be multiplied by a constant depending on the dimensions of the apparatus to give the kinematic viscosity in absolute units (stokes). In view of the range of viscosities met with, it is convenient to multiply these figures by 100 and to quote ν in centistokes.

A convenient range of values for R_c is from about 0.03 to 0.08 cm. R_w is conveniently about 0.25 cm. and L about 20 cm.

For most materials the fixing of h_0/h at 2.0 as described in the technique proposed above avoids the trouble of plotting any graphs, but where samples are very meagre, or very anomalous in behaviour, the $t/\log h_0/h$ curve should be plotted. An empirical figure representing the extent of the viscous anomaly is then conveniently obtained by plotting logs of both expressions, the extent to which the slope of the log-log curve differs from unity being a measure of the extent of the viscous anomaly. (For further explanation, see Scott Blair [1938].)

Table 1. *Variation of $t/\log h_0/h$ with time, for water*

t (sec.)	2	4	6	8	10	12	14	16	18	20	22
$t/\log h_0/h$	23.2	21.6	21.3	21.5	22.0	21.8	21.8	21.9	21.8	21.8	21.1

Table 2. *The effect of progressive shearing and resting on $t/\log h_0/h$ for human colostrum*

	t (sec.)	2	4	6	8	10	12	14	15	16	18	20	22	24
Shear No. 1	250	266	286	276	277	279	280	—	271	265	267	275	282	
2	—	235	—	242	—	266	—	—	271	—	278	—	282	
3	—	—	286	—	—	279	—	—	—	272	—	—	289	
4	—	—	—	—	—	—	—	263	—	—	—	—	—	
5*	—	—	—	—	—	—	—	—	—	—	—	—	—	
	t (sec.)	26	28	30	32	34	36	38	40	42	44	45	46	48
Shear No. 1	279	—	280	—	278	—	280	—	282	—	—	—	270	—
2	—	277	—	278	—	283	—	280	—	286	—	—	—	282
3	—	—	297	—	—	290	—	—	282	—	—	—	—	288
4	—	—	270	—	—	—	—	—	—	—	281	—	—	—
5*	—	—	263	—	—	—	—	—	—	—	—	—	—	—
	t (sec.)	50	52	54	56	60	64	66	68	72	75	76	78	80
Shear No. 1	274	—	—	—	—	—	—	—	—	—	—	—	—	—
2	—	278	—	280	279	281	—	282	287	—	284	—	—	285
3	—	—	289	—	290	—	290	—	296	—	—	291	—	—
4	—	—	—	—	276	—	—	—	—	281	—	—	—	—
5*	—	—	—	—	267	—	—	—	—	—	—	—	—	—
	t (sec.)	84	88	90	96	102	105	108	114	120	126	132	135	138
Shear No. 1	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2	287	292	—	—	—	—	—	—	—	—	—	—	—	—
3	291	—	290	292	293	—	294	290	294	294	293	—	—	295
4	—	—	283	—	—	281	—	—	285	—	—	289	—	—
5*	—	—	278	—	—	—	—	—	281	—	—	—	—	—
	t (sec.)	144	150	156	165	180	195	210	225	240	255	270	285	300
Shear No. 1	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2	—	—	—	—	—	—	—	—	—	—	—	—	—	—
3	299	299	294	—	—	—	—	—	—	—	—	—	—	—
4	—	291	—	290	294	296	296	297	297	294	294	297	300	
5*	—	283	—	—	290	—	296	—	296	—	311	—	313	

* After standing for $1\frac{1}{2}$ hr., having been gently stirred after $\frac{1}{2}$ hr.

EXPERIMENTAL

As a check on the accuracy of one of these viscosimeters an experiment was done with pure distilled water. The values of $t/\log h_0/h$ are given in Table 1. They are satisfactorily constant. Some materials show a tendency for the viscosity to fall as a result of repeated shearing [Scott Blair *et al.* 1939]. This makes it hard to decide on any unique value for viscosity. In some cases, the viscosity is partially recovered on standing (thixotropy or false-body). It has been shown (Table 2) that these properties are not present to any marked extent in the case of normal human mammary secretions. Progressive shearing and resting are seen to have little or no effect on this flow curve for a colostrum milk sample.

It is not intended to publish here any large number of data or to discuss their bearing on clinical problems. This is being done in another article [Waller *et al.* 1941]. A few typical curves only will be given. These are shown in Fig. 2.

Fig. 2.

	No.	$t/\log h_0/h$	η	Notes
○	14	46	1.44	5th day milk, 2nd para.
×	15	394	12.35	38 weeks (about due), 1st para.
△	18	204	6.40	38 weeks, 1st para.
□	20	668	20.8	Just after delivery, 1st para.
+	21	470	14.7	3rd day milk, 1st para.
▽	22	42	1.31	4th day milk (engorgement), 1st para.
●	23	236	7.38	38 weeks, 1st para.

It will be seen that the curves are very nearly but not quite linear (a few samples showed even more marked anomalies), and that the viscosities varied over a wide range. Although no such extreme samples appear in the figure, values as high as 100 centistokes have been obtained for prenatal secretions, compared with an average of about 1.3 centistokes for normal milks.

The fall in viscosity with rising shearing stress is gradual. There is no sign of a yield value, which leads to the conclusion that all these secretions would

flow through any uncontrolled orifice even at very low pressure. The prevention of seepage thus depends on the behaviour of the ducts rather than on the properties of the secretion even when viscosity is very high.

SUMMARY

1. A method is described by which the viscosity and viscous anomalies of small (1 ml.) samples of human mammary secretions may be quickly and accurately determined.

2. These secretions, tested at blood heat, behave in general surprisingly like true fluids, i.e. their viscosities differ but little with varying shearing stress. The viscosities themselves vary over a very wide range—at least a hundredfold.

3. Where viscous anomalies exist, they appear as a gradual fall in viscosity with rising stress, suggesting that even the most viscous materials would flow slowly under extremely small pressures.

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