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Texture Study on Optimum Formulation of Molded Poultices[1,2]

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In the previous paper, the value (x_i) of the i'th physical property of a molded poultice was measured, the preference value (y_j) for the j'th textural characteristic was obtained in sensory tests, and a mathematical expression for the relation between y_j and x_i was obtained in the form of first-order regression equations with good regression coefficients. A study was performed to ascertain whether x_i is related to and can be obtained from the quantities, a_k, of components, k, in a preparation. Molded poultices of 53 formulations containing various quantities of nine ingredients were prepared and their physical properties were measured. For seven of their properties, the relations between x_i and a_k were analyzed by stepwise multiple regression analysis and were obtained in the form of first-order regression equations with a confidence level above 95%. These relations made it possible to carry out simulation of the optimum formulations of molded poultices. One of the simulated optimum formulations showed viscoelasticity at 50 °C obeying the four-element model, whose values were determined from creep test data.

Keywords——molded poultice; textural characteristic; quantity; optimum formulation; rheological model

The purpose of this work is to contribute to the design of molded poultices in the light of textural and physicochemical considerations. The preceding paper[1] was concerned with the following relations: (1) y_j–x_i, (2) Y–y_j, (3) Y–x_i, where x_i is the i'th physical property of a molded poultice, y_j is the preference value of a subject treated with the poultice for the j'th textural characteristic, Y is the degree of overall preference for a molded poultice on the basis of sensory assessments, and a_k is the quantity of ingredient k in a preparation. Relation (1) was obtained in the form of first-order regression equations with a good correlation coefficient for each of the seven textural characteristics (y_j). Overall preference (Y) for a molded poultice seemed to depend on the area of skin treated and the season, so that a fixed relation (2) could not be obtained. It should be feasible to set up this relation in advance according to the intended purpose of the poultice. Relation (3) could then be obtained from relations (1) and (2). If another relation, (4), between x_i and a_k, is obtained, the overall preference, (Y), and the individual parameter preferences, (y_j), can be expressed in terms of a_k.

Experimental

Materials——The materials used to prepare the molded poultices are listed in Table I and are of the same grades as in the previous paper.[1]

Preparation of Molded Poultices——Fifty three formulations of molded poultices containing various quantities of nine ingredients, whose ranges are summarized in Table I, were prepared by the procedure reported in the previous paper.[1] Three formulations selected from the 53 preparations are shown as A, B, and C in Table II. Each formula was prepared in an amount of 5 kg, since preliminary studies on a 1 kg scale confirmed that satisfactory molded poultices could be obtained.

TABLE I. Ranges of Component Contents of 53 Formulations

Components	Formulations (%, w/w)		
	a_{min}—a_{max}	$\bar{a}$ Average	σ_a Standard deviation
a_1, gelatin	0—1.43	0.2158	0.5168
a_2, propylene glycol	8.34—20.0	10.10	4.2142
a_3, sorbitol (70% aq. solution)	0—11.92	10.12	4.3080
a_4, polyvinyl alcohol	1.0—4.5	3.169	0.9163
a_5, sodium polyacrylate	0—1.5	0.9321	0.4362
a_6, magnesium dichloride	0—3.5	0.5283	1.2650
a_7, alum	0—0.14	0.0423	0.06488
a_8, polybutene	6.0—9.0	7.7547	1.4924
a_9, kaolin	40—46	42.468	1.7246
a_{10}, minor constituents	1.27	1.27	0.0
a_{11}, essential oil[a)]	3.8	3.8	0.0
a_{12}, water	Added to 100%		

a) The essential oil contained *dl*-camphor (21%, w/v), *l*-menthol (24%), methyl salicylate (24%), and peppermint oil (31%).

TABLE II. Some Formulations of Molded Poultices

Components	Formulations (%, w/w)		
	A	B	C
a_1	1.43 (2.35)	0.0 (−0.418)	0.0 (−0.418)
a_2	8.34 (−0.418)	8.34 (−0.418)	8.34 (−0.418)
a_3	11.92 (0.418)	11.92 (0.418)	11.92 (0.418)
a_4	1.0 (−2.37)	2.37 (−0.873)	3.5 (0.361)
a_5	0.0 (−2.14)	0.0 (−2.14)	1.5 (1.302)
a_6	3.5 (2.35)	3.5 (2.35)	0.0 (−0.418)
a_7	0.14 (1.505)	0.14 (1.505)	0.0 (−0.652)
a_8	9.0 (0.838)	9.0 (0.838)	6.0 (−1.176)
a_9	42.09 (−0.220)	42.09 (−0.220)	46.0 (2.048)
a_{10}	1.27	1.27	1.27
a_{11}	3.8	3.8	3.8
a_{12}	Added to 100%		

( ) indicates the standardized quantity.

Measurements of Properties Representative of Textural Characteristics and of Rheological Properties——The representative properties, peeling (x_1), tackiness (x_2), stickiness (x_3), and "Dare" (x_4) were observed in the same manner and using the same measuring instruments as were described in detail in the previous paper.[1)] The rheological properties, yield value (x_5), average viscosity (x_6), and hysteresis loop area (x_7) were also observed in the way reported in the previous paper.[1)]

Creep Testing——The rheological model of the paste of a molded poultice was examined using a consistometer, shown schematically in Fig. 1 (Haake, Konsistometer, type KON), as a creep testing apparatus. The sample cell was composed of two parts: an outer cell containing the sample paste, with a diameter of 2.00 cm, and a moveable inner cell with a hole having a length of 2.0 cm and a diameter of 0.25 cm. A constant pressure of 1.053×10^5 dyn/cm^2 was applied to the upper part of the inner cell, and this pushed the paste through the hole from the outer cell into the inner cell. The volume change of the paste remaining in the outer cell was monitored by observing the variation of the position of the inner cell to an accuracy of 10^{-3} cm. The creep curve obtained was analyzed by the method of Nakagawa and Kanbe.[3)]

Multiple Regression Analysis——Stepwise multiple regression analysis was performed as follows to obtain the relation, (4), between x_i and a_k. (I) The quantities a_k were standardized using Eq. 1.

$$a_k^* = (a_k - \bar{a}_k)/\sigma_k \quad (1)$$

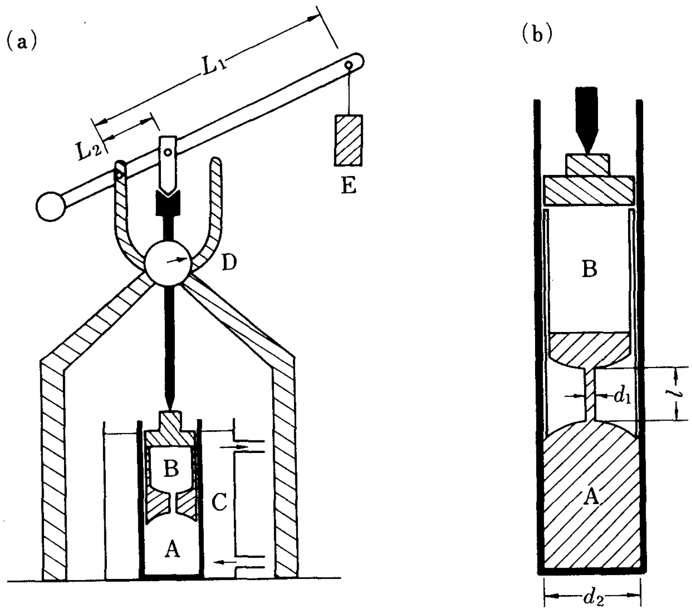

Fig. 1. Schematic Drawing of (a) Creep Testing Apparatus and (b) Sample Cell

The sample cell (b) is composed of an outer cell (A) and an inner cell (B), which are kept at 50±0.1 °C using a water jacket (C). A gauge (D) shows the position of the inner cell to an accuracy of 10^{-3} cm. The weight of E is 150 g and the arms, L_1 and L_2, are 45.0 and 5.0 cm long, respectively. The diameter of the outer cell (d_2) is 2.0 cm and that of the hole of the inner cell (d_1) is 0.25 cm. The length of the hole (l) is 2.0 cm.

TABLE III. Design for Stepwise Multiple Regression Analysis

Formulation number	Independent variables a_1^*	a_2^*	a_k^*	$\cdots$	a_9^*	Dependent variables x_1^*	x_2^*	x_i^*	$\cdots$	x_7^*
1	a_{11}^*	a_{21}^*	a_{k1}^*	$\cdots$	a_{91}^*	x_{11}^*	x_{21}^*	x_{i1}^*	$\cdots$	x_{71}^*
2	a_{12}^*	a_{22}^*	a_{k2}^*	$\cdots$	a_{92}^*	x_{12}^*	x_{22}^*	x_{i2}^*	$\cdots$	x_{72}^*
3	a_{13}^*	a_{23}^*	a_{k3}^*	$\cdots$	a_{93}^*	x_{13}^*	x_{23}^*	x_{i3}^*	$\cdots$	x_{73}^*
.	.	.	.	$\cdots$	.	.	.	.	$\cdots$	.
l	.	.	a_{kl}^*	$\cdots$	.	.	.	x_{il}^*	$\cdots$	.
.	.	.	.	$\cdots$	.	.	.	.	$\cdots$	.
53	a_{153}^*	a_{253}^*	a_{k53}^*	$\cdots$	a_{953}^*	x_{153}^*	x_{253}^*	x_{i53}^*	$\cdots$	x_{753}^*

An asterisk * indicates a standardized value.

a_k^*, $\bar{a}_k$, and σ_k are the standard normal variates,[4] the mean values, and the standard deviation of a_k, respectively. (II) The properties of molded poultices, x_i, were standardized in the same way. (III) The relation (4), between x_i and a_k, was calculated as

$$x_i^* = c_{0i} + c_{1i}a_1^* + \cdots + c_{ki}a_k^* + \cdots + c_{9i}a_9^* \tag{2}$$

where c_{ki} is the correlation coefficient. This c_{ki} was obtained by using a computer (Burroughs, B 7800) with a program package[5] for stepwise multiple regression analysis (F value for inclusion = 0.01, F value for deletion = 0.005). Table III shows the design of this analysis with variables a_k^* and x_i^* for 53 preparations. Taking the x_i^* as an example,

$$x_{11}^* = c_{01} + c_{11}a_{11}^* + \cdots + c_{k1}a_{k1}^* + \cdots + c_{91}a_{91}^*$$

$$x_{12}^* = c_{01} + c_{11}a_{12}^* + \cdots + c_{k1}a_{k2}^* + \cdots + c_{91}a_{92}^*$$

$$— \quad — \quad \cdots \quad — \quad \cdots \quad —$$

$$x_{1l}^* = c_{01} + c_{11}a_{1l}^* + \cdots + c_{k1}a_{kl}^* + \cdots + c_{91}a_{9l}^*$$

$$— \quad — \quad \cdots \quad — \quad \cdots \quad —$$

$$x_{153}^* = c_{01} + c_{11}a_{153}^* + \cdots + c_{k1}a_{k53}^* + \cdots + c_{91}a_{953}^*$$

The ten correlation coefficients c_{k1} were obtained from these 53 equations using a computer.

Results and Discussion

Properties of Molded Poultices

These 53 formulations were prepared and the poultices were used for sensory tests with-

Table IV. Ranges of Values of the Physical Properties of 53 Formulations

Physical properties	x_{min}—x_{max}	$\bar{x}$ Average	σ_x
x_1	0—0.72	0.0866	0.1514
x_2	10—136	67.5	36.89
x_3	0—1.9	0.219	0.4652
x_4	0—26	14.46	11.08
x_5	27—252	84.0	49.03
x_6	374—2331	868.6	418.3
x_7	11.9—122.8	34.16	20.71

x_5, yield value ($\times 10^4$ dyn/cm^2) and x_7, hysteresis loop area ($\times 10^7$ dyn/cm$^2\cdot$s).

Table V. Experimental (ex) and Predicted (pr) Values of Physical Properties for Formulations A, B, and C

Physical properties	Formulation A	B	C
	ex–pr	ex–pr	ex–pr
x_1	0.26–0.28	0.01–0.22	0.07–0.12
x_2	46–64	126–112	98–91
x_3	0.14–1.03	0.48–1.03	0.04–0.06
x_4	26–25	26–25	4–7
x_5	61–66	140–140	69–50
x_6	750–720	1400–1350	800–800
x_7	39–46	66–62	25–28

x_5, yield value ($\times 10^4$ dyn/cm^2) and x_7, hysteresis loop area ($\times 10^7$ dyn/cm$^2\cdot$s).

out any difficulty. The representative properties, x_1—x_4, and the rheological properties, x_5—x_7, were observed and are summarized in Table IV. The properties of representative poultices A, B, and C are shown in Table V.

Results of Multiple Regression Analysis

The results of multiple regression analysis and of variance analysis are shown in Table VI, and indicate high confidence levels, above 95%, for each regression equation. For example, x_1^*, obtained from Eq. 3, shows a confidence level of 97.39%, as shown in Table VI.

$$x_1^* = 0.0065 + 0.1609a_1^* - 0.1704a_3^* + 0.5670a_6^* - 0.1640a_7^* - 0.1222a_8^* + 0.0868a_9^* \quad (3)$$

This equation yields desirable values for peeling characteristic when the amounts of a_6 (magnesium dichloride), a_1 (gelatin), and a_9 (kaolin) decrease, and the amounts of a_3 (sorbitol), a_7 (alum), and a_8 (polybutene) increase. Table VI shows that increasing the quantity of a_8 (polybutene) gives higher values for the rheological parameters (x_5, x_6, and x_7). When the amount of the tackifier a_8 is increased, the network structure of the formulation becomes more rigid so that the peeling characteristic improves.[6] When the amount of magnesium dichloride (a_6) is increased, the paste becomes tacky and sticky (the values of x_2 and x_3 are increased) but peelability deteriorates (the value of x_1 is increased), as shown in Table VI. Hence, the quantity of each ingredient of a molded poultice must be chosen to provide an appropriate blend of properties in the final product.

The values of x_i predicted by means of these equations were compared with the

TABLE VI. Optimum Regression Equation for Physical Properties Determined by Stepwise Multiple Regression Analysis

	$x_i^*=c_{0i}+c_{1i}a_1^*+c_{2i}a_2^*+c_{3i}a_3^*+\cdots+c_{9i}a_9^*$						
	x_1^*	x_2^*	x_3^*	x_4^*	x_5^*	x_6^*	x_7^*
c_0	0.0065	−0.0021	−0.0184	0.0281	−0.0054	−0.0004	−0.0083
c_1	0.1609	−0.2718	—	—	−0.5343	−0.5379	−0.4858
c_2	—	—	—	—	—	−0.6591	−0.3846
c_3	−0.1704	—	—	—	0.5730	—	—
c_4	—	0.3965	—	—	—	—	—
c_5	—	0.2977	—	—	—	—	—
c_6	0.5670	0.8373	0.7508	—	—	—	0.1781
c_7	−0.1640	0.3450	—	0.5065	—	—	—
c_8	−0.1222	−0.4856	—	0.2864	0.8024	0.8104	0.6928
c_9	0.0868	—	—	—	0.1281	0.1728	0.1076
Analysis of variance table							
Degrees of freedom							
regression	6	6	1	2	4	4	5
residual	46	46	51	50	48	48	47
total	52	52	52	52	52	52	52
F ratio	2.673	24.594	66.118	25.825	12.308	15.422	7.009
Conf. level	97.39	100	100	100	100	100	99.99

experimental values for preparations A, B, and C in Table V and reasonable agreement was found. The regression equations in Table VI provided good predicted values of x_i.

Optimum Formulation

x_i was expressed in terms of a_k from the results in Table VI, and the relation (1) between y_j and x_i was obtained in the previous study,[1)] so that y_j could be expressed as

$$y_j^*=b_{0j}+b_{1j}a_1^*+\cdots+b_{kj}a_k^*+\cdots+b_{9j}a_9^* \qquad (4)$$

where b_{kj} is a regression coefficient. These equations are given in Table VII, where a poultice showing a higher value of y_j has more satisfactory textural characteristics. For example, a higher value of y_1 (peeling) is more acceptable. Furthermore, the varieties of a_k in Eq. 4 are the standard normal varieties so that they are under the same influence. The quantities of the ingredients with higher values of b_{kj} have greater effects on the characteristic y_j. For example, peeling (y_1) can be improved by increasing the amount of sorbitol (a_3) and by decreasing that of magnesium dichloride (a_6), which causes a deterioration of the tackiness (y_2). The ratio of y_1 to y_2 ought to be established according to the design and intended use of the molded poultice, and then the quantities of the ingredients should be chosen.

The values of y_j for poultices A, B, and C were calculated by means of the Eqs. in Table VII, and are given in Table VIII.

Poultice A is a poor one showing negative values for y_1—y_5. Poultice B, containing polyvinyl alcohol instead of gelatin, has improved tackiness (y_2), while poultice C, which contains sodium polyacrylate, shows good values for y_1—y_7. These results agree with the experimental data (Table V).

Relation (2) between Y and y_j must be set up in advance according to the intended purpose of the molded poultice, and then optimum formulations can be obtained with Eq. 4,

Table VII. Optimum Regression Equation for Textural Characteristics

$$y_j^* = b_{0j} + b_{1j}a_1^* + b_{2j}a_2^* + b_{3j}a_3^* + \cdots + b_{9j}a_9^*$$

	y_1^*	y_2^*	y_3^*	y_4^*	y_5^*	y_6^*	y_7^*
b_0	0.6570	0.1942	−0.2989	−0.2706	−0.2750	0.8016	1.4741
b_1	−0.1528	−0.6707	—	—	—	—	−0.4533
b_2	—	—	—	—	—	—	—
b_3	0.1616	—	—	—	—	—	−0.4860
b_4	—	0.9784	—	—	—	—	—
b_5	—	0.7346	—	—	—	—	—
b_6	−0.5374	2.0662	−1.7430	−1.5780	−1.6040	—	—
b_7	0.1553	0.8514	—	—	—	−0.2009	−0.0808
b_8	0.1159	−1.1983	—	—	—	−0.1136	−0.7263
b_9	−0.082	—	—	—	—	—	−0.1087

Table VIII. Average Preferences Calculated from the Regression Equations

Textural characteristics	Formulations A	B	C	D[a)]
y_1^*	−0.548	−0.126	0.474	0.771
y_2^*	−0.139	3.181	1.773	2.325
y_3^*	−4.395	−4.395	0.430	0.430
y_4^*	−3.979	−3.979	0.389	0.389
y_5^*	−4.044	−4.044	0.395	0.395
y_6^*	0.405	0.405	1.067	1.097
y_7^*	−0.502	0.752	2.548	1.964

a) Formulation D; propylene glycol 2.3%, sorbitol 15.8%, PVA 3.4%, sodium polyacrylate 1.7%, polybutene 5.6%, kaolin 45%, minor constituents 1.27%, essential oil 3.8%, and water added to 100%.

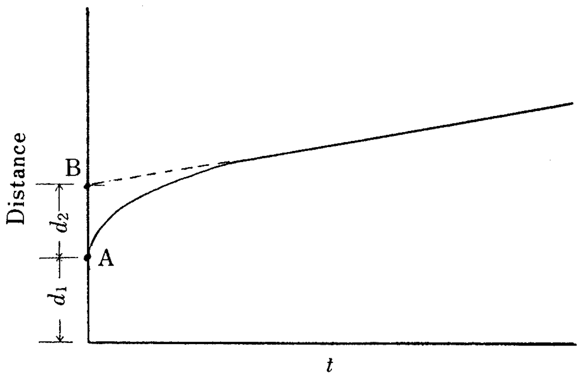

Fig. 2. Schematic Drawing of a Creep Curve for Formulation D at 50 °C

The distance, d, that the inner cell descended in a time of t s was measured with gauge D as shown in Fig. 1. The distance at point A (d_1) is 1.419 cm, and that at point B (d_1+d_2) is 2.052 cm. B is the point where the back-extrapolation of this creep curve crosses the ordinate. Thus,

$$d_{t=\infty} = 2.052 + 2.356 \times 10^{-4} t$$

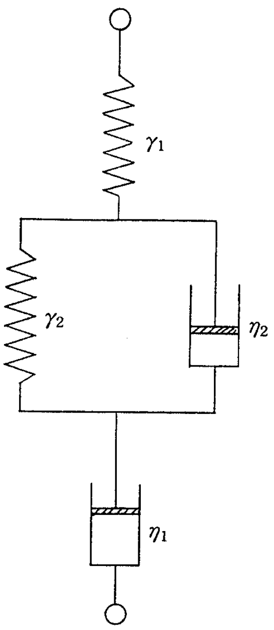

Fig. 3. Four-Element Model Representing the Behavior of a Viscoelastic Material

The creep of formulation D in Fig. 2. is given by this model with $\gamma_1 = 74000\,\text{dyn/cm}^2$, $\gamma_2 = 1.66 \times 10^5\,\text{dyn/cm}^2$, $\eta_2 = 2.02 \times 10^5\,\text{P}$, and $\eta_1 = 1700\,\text{P}$.

as shown in Table VII, using a computer. For example, formulation D in Table VIII was obtained mathematically and appears to be one of the optimum formulations in which tackiness (y_2)is emphasized. One kilogram of D was prepared without difficulty and showed satisfactory characteristics in a sensory test.

Rheological Model of the Paste

The formulation D paste in Table VIII was studied rheologically to ascertain whether a four-element model composed of two springs as elastic elements and two dashpots as viscous elements could adequately describe the viscoelastic behavior of the paste as determined by using the creep testing apparatus at 50 °C (although viscosity was observed at 37 °C with a cone-plate viscometer). The paste in the outer cell at 37 °C could not move into the inner cell through the hole of the inner cell when the same pressure was exerted. A creep curve was observed for sample D immediately after preparation at 50 °C and is shown in Fig. 2. This curve could be analyzed (in terms of a four-element model consisting of: Hookean elasticity (γ_1), 74×10^3 dyn/cm^2; Voight element of elasticity (γ_2), 1.66×10^5 dyn/cm^2; Voight element of viscosity (η_2), 2.02×10^5 P; and Newtonian viscosity (η_1), 1700 P (Fig. 3). The average viscosity (x_6) of molded poultices A, B, and C (Table V) is between 750 and 1400 P at 37 °C, at a shear rate of about 400 s^{-1} using a cone-plate viscometer. A η_1 value of 1700 P was obtained at 50 °C by creep testing at a shear rate of about 2 s^{-1}, which may correspond to laminar flow of the paste moving in the hole according to Haagen–Poiseuille's law. The difference between the values of x_6 and η_1 was probably caused by the thixotropy, shear, and temperature dependency of the rheological properties.

Conclusion

Fifty-three formulations of molded poultices were prepared, and their physical properties (x_i) were measured. The relations of x_i to the quantities, a_k, of the ingrediens, k, were expressed as first-order regression equations with a confidence level above 95%. Using these equations and the results previously obtained for the relation between preference value (y_j) and x_i, y_j was found to be related to a_k. It is possible to carry out mathematical simulation to obtain optimum formulations of molded poultices on the basis of textural studies using the quantities a_k. One of the simulated optimum formulations showed viscoelasticity at 50 °C obeying a four-element model. The values of the elements were determined by creep testing.

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