Configuration and interactions of the polar head group in gangliosides

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1. The interactions of gangliosides with Ca^{2+} and some polar-head-group requirements for establishment of particular interactions with phosphatidylcholine were studied in monolayers at the air/145 mM-NaCl interface. 2. Ganglioside- Ca^{2+} interactions, as revealed by surface-potential measurements, depended on the position occupied by sialosyl residues in the oligosaccharide chain. The interactions with Ca^{2+} of the single sialosyl residue of monosialogangliosides occurred above 0.1 mM- CaCl_2 , whereas the interaction of the cation with additional sialosyl groups in di- or tri-sialogangliosides depended on the carbohydrate residue to which the sialosyl moiety was attached. The sialosyl residue bound in sialosyl-sialosyl linkage interacted very little with Ca^{2+} . The sialosyl residue attached to the terminal galactose of the neutral tetrasaccharide chain interacted with Ca^{2+} above 1 μM - CaCl_2 . 3. Experiments with mixed monolayers containing dihexadecyl phosphate and hexadecyltrimethylammonium indicated that for the occurrence of interactions of polysialogangliosides with phosphatidylcholine characterized by reductions in molecular packing and surface potential both charged groups of the phospholipid and sialosyl residues with particular dipolar properties in the ganglioside are participating. 4. Possible configurations that can explain the behaviour in monolayers were inspected with space-filling molecular models. The position of the carboxylate group of sialosyl residues with respect to the interface and to the sialosyl molecular plane can explain the different orientation of the dipole-moment vector of this residue, which depends on the position to which it is linked in the oligosaccharide chain. Favoured interactions of polysialogangliosides with phosphatidylcholine may result from a configuration allowing a partial matching of two oppositely oriented electrical vectors contributed by the zwitterionic phosphocholine group and particular sialosyl groups.

Monosialogangliosides have in most cases the sialosyl residue attached to the galactosyl group (proximal galactose) of the lactosyl moiety linked to ceramide. Gangliosides having more than one sialosyl group have these attached either to the first sialosyl group or to the galactosyl moiety (distal

galactose) that usually is at the end of the neutral carbohydrate chain. In monomolecular films of gangliosides spread at the air/145 mM-NaCl interface the dipolar properties of the different sialosyl residues depend on their position along the oligosaccharide chain (Maggio *et al.*, 1978a). These different interfacial properties can also be correlated with the type of interactions exhibited by polysialogangliosides in mixed monolayers with phospholipids compared with those found for monosialogangliosides or neutral glycosphingolipids (Maggio *et al.*, 1978b).

Abbreviations used: AcNeu, *N*-acetylneuraminate; Cer, ceramide (*N*-acylsphingoid); GlcCer; Glc β 1 $\rightarrow$ 1Cer; Gg₄Cer, Gal β 1 $\rightarrow$ 3GalNAc β 1 $\rightarrow$ 4Gal β 1 $\rightarrow$ 4Glc β 1 $\rightarrow$ 1Cer; G_{M3}, NeuGc α 2 $\rightarrow$ 3Gal β 1 $\rightarrow$ 4Glc β 1 $\rightarrow$ 1Cer; G_{D3}, NeuAc α 2 $\rightarrow$ 8NeuAc α 2 $\rightarrow$ 3Gal β 1 $\rightarrow$ 4Glc β 1 $\rightarrow$ 1Cer; G_{M1}, Gal β 1 $\rightarrow$ 3GalNAc β 1 $\rightarrow$ 4Gal(3 $\leftarrow$ 2 α NeuAc) β 1 $\rightarrow$ 4Glc β 1 $\rightarrow$ 1Cer; G_{D1a}, NeuAc α 2 $\rightarrow$ 3Gal β 1 $\rightarrow$ 3GalNAc β 1 $\rightarrow$ 4Gal(3 $\leftarrow$ 2 α NeuAc) β 1 $\rightarrow$ 4Glc β 1 $\rightarrow$ 1Cer; G_{T1}, NeuAc α 2 $\rightarrow$ 3Gal β 1 $\rightarrow$ 3GalNAc β 1 $\rightarrow$ 4Gal(3 $\leftarrow$ 2 α NeuAc8 $\leftarrow$ 2 α NeuAc) β 1 $\rightarrow$ 4Glc β 1 $\rightarrow$ 1Cer. Abbreviations are those recommended by IUPAC-IUB (cf. Maggio *et al.*, 1978a) for neutral glycosphingolipids and by Svennerholm (1963) for gangliosides.

In the present work possible configurations that can explain the behaviour in monolayers are investigated employing space-filling Corey-Pauling-Koltun molecular models. In addition, results from lipid-monolayer experiments showed that interactions of gangliosides with Ca^{2+} are dependent on

the position of a sialosyl residue in the polar head group of the ganglioside as revealed by changes in the surface potential. Also, some polar-head-group requirements for the establishment of particular interactions of gangliosides with phosphatidylcholine were investigated.

Materials and methods

The source and purity of the lipids used were as described previously (Maggio *et al.*, 1978a,b). Dihexadecyl phosphate was from K & K Laboratories, Plainview, NY, U.S.A., and hexadecyltrimethylammonium bromide from BDH, Poole, Dorset, U.K. The surface pressures, molecular areas and surface potentials of lipid monolayers were recorded automatically as described previously (Maggio *et al.*, 1978a). All subphases contained unbuffered 145 mM-NaCl, and in some experiments CaCl_2 in the concentration indicated was also present. The pH was adjusted to 5.6 or 1.2 before spreading the monolayer at $20 \pm 1^\circ\text{C}$. The behaviour of mixed films was analysed by comparing deviations from the additivity rule in molecular area or surface potential per molecule at a given surface pressure as described elsewhere (cf. Gaines, 1966; Maggio *et al.*, 1978b). Results are given as averages of duplicate or triplicate runs. Reproducibility was within $\pm 0.02 \text{ nm}^2$ for surface areas, within $\pm 1 \text{ mN} \cdot \text{m}^{-1}$ for surface pressures and within $\pm 5 \text{ mV}$ for surface potentials.

Results

Ganglioside- Ca^{2+} interactions

Provided measurements are compared at constant area per molecule, the changes of surface potential of lipid monolayers induced by Ca^{2+} in the subphase can give information on specific interactions of the bivalent cation with anionic groups in the polar head of a lipid (cf. Bangham, 1968; Maggio & Lucy, 1976). The variation in molecular area for each type of ganglioside induced by the addition of Ca^{2+} to a subphase containing 145 mM-NaCl was less than 5% (results not shown). Fig. 1(a) shows the changes in surface potential obtained for monolayers of Gg_4Cer and gangliosides G_{M1} , G_{M3} , G_{D3} , G_{D1a} and G_{T1} at $30 \text{ mN} \cdot \text{m}^{-1}$ on subphases containing Ca^{2+} in different concentrations, in addition to 145 mM-NaCl, pH 5.6. For all gangliosides the increase in Ca^{2+} concentration produced an increase in surface potential. However, as the area per molecule of the different types of gangliosides is different (Maggio *et al.*, 1978a) the results in Fig. 1(a) cannot be compared directly, since the different molecular surface densities contribute to the value of the surface potential in each case. For this reason, the results are analysed in the form of average surface potential per molecule ($\Delta V/n$), where n is the number of molecules/ cm^2 , calculated from $\Delta V/n = 10^{-14} \cdot \Delta V \cdot A$ ($\text{mV} \cdot \text{nm}^2 \cdot \text{molecule}^{-1}$) (cf. Shah, 1970; Maggio *et al.*, 1978a).

Fig. 1(b) shows the surface potentials per molecule of the different gangliosides on subphases

Fig. 1. Effect of Ca^{2+} ions on the surface potential of ganglioside monolayers

The values of surface potential (ΔV) in (a) were obtained at $30 \text{ mN} \cdot \text{m}^{-1}$ from surface potential-area isotherms on subphases of 145 mM-NaCl, pH 5.6, containing CaCl_2 at the concentration indicated. $(\Delta V/n)_{\text{Ca}}$ on the ordinate of (b) represents the mean surface potential per molecule on subphases containing CaCl_2 after discounting the corresponding value on 145 mM-NaCl. For (a) and (b): $\times$, Gg_4Cer ; $\bullet$, ganglioside G_{M1} ; Δ , ganglioside G_{M3} ; $\circ$, ganglioside G_{D3} ; $\square$, ganglioside G_{D1a} ; $\blacksquare$, ganglioside G_{T1} . $(\Delta V/n)_{\text{Ca}}$ on the ordinate of (c) represents the contribution of each type of sialosyl residue to the total change of surface potential per molecule. The results have been obtained from data in (b) by subtracting the value of Gg_4Cer from those for ganglioside G_{M1} , for AcNeu_1 ($\bullet$); the values for ganglioside G_{M1} for those for ganglioside G_{D1a} , for AcNeu_2 ($\square$); and the values for gangliosides G_{D1a} or G_{M3} from those for gangliosides G_{T1} or G_{D3} respectively for AcNeu_3 ($\blacksquare$ and $\circ$). For denomination of sialosyl residues see the legend to Plate 1. Although qualitatively similar to those shown, all the changes were dependent on the molecular packing and more marked at lower pressures.

containing increasing concentrations of Ca^{2+} , in addition to NaCl, after discounting the value of $\Delta V/n$ obtained for each ganglioside on subphases containing NaCl only. These values therefore represent the change in $\Delta V/n$ induced by Ca^{2+} and since neutral glycosphingolipids such as Gg_4Cer did not show changes in surface potential in these conditions, the interactions can be ascribed to the presence of sialosyl residues in the polar head group of the gangliosides. Fig. 1(b) shows that, as for the dipolar contributions (Maggio *et al.*, 1978a), the type of interactions with Ca^{2+} depend on the positions occupied by the sialosyl groups in the oligosaccharide chain and not only on their number. Thus, the interaction of the bivalent cation with ganglioside G_{D1a} having two sialosyl residues is already apparent at $1\mu\text{M}\text{-CaCl}_2$, whereas practically no interaction is detected with monosialogangliosides G_{M1} or G_{M3} at less than $0.1\text{mM}\text{-CaCl}_2$. Trisialoganglioside G_{T1} shows changes comparable with those of ganglioside G_{D1a} , whereas disialoganglioside G_{D3} has an intermediate behaviour that becomes more similar to that of monosialogangliosides at greater than $1\text{mM}\text{-CaCl}_2$.

If the interaction of Ca^{2+} with a particular sialosyl residue is assumed to remain unchanged in ganglioside polar head groups containing more than one sialosyl moiety, the contribution of the different sialosyl- Ca^{2+} interactions to the total change in surface potential per molecule can be calculated. This is shown in Fig. 1(c) by subtracting

the values shown in Fig. 1(b) for ganglioside G_{D1a} from those for ganglioside G_{M1} , in order to investigate the interaction with Ca^{2+} of the sialosyl residue (AcNeu₂) attached to the galactose residue distal to ceramide. The interaction of Ca^{2+} with the sialosyl residue attached in sialosyl-sialosyl linkage (AcNeu₃) has been calculated by subtraction of the values obtained for gangliosides G_{T1} or G_{D3} from those for gangliosides G_{D1a} or G_{M3} respectively. The results thus obtained indicate that the interaction of AcNeu₂ with Ca^{2+} occurs at a concentration of bivalent cation three orders of magnitude lower than that required for noticeable interactions with the sialosyl residue bound to the galactose residue proximal to ceramide (AcNeu₁), whereas AcNeu₃, if it interacts with Ca^{2+} , produces less changes in $\Delta V/n$ than AcNeu₂, either in di- or tri-sialogangliosides.

Polar-head-group requirements for ganglioside-phosphatidylcholine interactions

It was previously found that di- and tri-sialogangliosides, but not monosialogangliosides, show interactions with phosphatidylcholine characterized by decreases (negative deviations from the non-interacting behaviour; Maggio *et al.*, 1978b) in mean molecular area and average surface potential per molecule on subphases of $145\text{mM}\text{-NaCl}$, pH 5.6. The mixtures of phosphatidylcholine with polysialogangliosides behaved as those with monosialogangliosides, if the mixed monolayers are studied on

Fig. 2. Deviations from ideal behaviour in mixed monolayers of sphingolipids with dipalmitoyl phosphatidylcholine, hexadecyltrimethylammonium and dihexadecyl phosphate

Percentage deviations (negative or positive) in mean molecular area (a) and mean surface potential per molecule (b) for mixed monolayers relative to the corresponding parameters for non-interacting films on $145\text{mM}\text{-NaCl}$, pH 5.6, are shown. The values represent deviations obtained at $30\text{mN}\cdot\text{m}^{-1}$ for mixed films, in molar ratio 1:1, of the sphingolipid indicated with: dipalmitoyl phosphatidylcholine (●, at pH 5.6; ▲, at pH 1.2); dihexadecyl phosphate (□); hexadecyltrimethylammonium (△); an equimolar mixture of dihexadecyl phosphate and hexadecyltrimethylammonium (○).

subphases of 145 mM-NaCl at pH 1.2, indicating that polar-head-anionic groups are participating in the different interactions (Figs. 2a and 2b). It is interesting that the modification of the pH in the subphase can control the surface packing, since the decreases in mean molecular area of polysialoganglioside/phosphatidylcholine mixtures are converted into positive deviations from the ideal behaviour at pH 1.2.

The interaction of glycosphingolipids with molecules that contain only one instead of the two charged groups of the phosphocholine moiety was studied in mixed monolayers with dihexadecyl phosphate or hexadecyltrimethylammonium. Figs. 2(a) and 2(b) show the percentage deviations from the non-interacting behaviour in mean molecular area and surface potential per molecule of mixed monolayers of the different glycosphingolipids with dihexadecyl phosphate or hexadecyltrimethylammonium. It is seen that the interactions obtained with these molecules are different from those found with phosphatidylcholine. Glycosphingolipids mixed in monolayers formed by an equimolar mixture of dihexadecyl phosphate and hexadecyltrimethylammonium, for which the interfacial region contains polar components essentially similar to those in a mixed film of glycosphingolipids with phosphatidylcholine, interacted almost identically to interactions with this phospholipid.

Discussion

The sialosyl residues attached to the oligosaccharide chain of the ganglioside molecule show dipolar properties that depend strongly on their position. In monosialogangliosides, the single sialosyl residue (AcNeu₁; see Plate 1) bound to the proximal galactose residue of the polar head group possesses a resultant dipole moment whose orientation with respect to the interface is opposite to that of the hydrophobic portion of the molecule. By contrast, the resultant dipole moment of the sialosyl residues attached in sialosyl-sialosyl linkage (AcNeu₃) or to the distal galactose residue (AcNeu₂) of the polar chain in di- and tri-sialogangliosides show orientations that are in the direction of that of the hydrophobic moiety and contrary to that of AcNeu₁. Also, from titration studies it was previously concluded that a negative charge on the carboxylate group of the sialosyl residues is at least one of the factors determining the direction of the resultant dipole-moment vector in these residues (Maggio *et al.*, 1978a). Possible molecular configurations that may be responsible for this behaviour were approximated by inspection of space-filling Corey-Pauling-Koltun molecular models.

Plate 1(a) represents a non-interacting mixture of

trisialoganglioside G_{T1} with dipalmitoyl phosphatidylcholine. For ganglioside G_{T1} the fundamental conformation of the ceramide moiety is represented essentially as proposed by Pascher (1976) with the rigid amide group, comprising six atoms in a planar conformation, oriented perpendicularly with respect to the axis of the two hydrocarbon chains and lying approximately at the air/water interface. A parallel chain stacking is achieved by a sharp perpendicular bend of the fatty acyl moiety around its second carbon atom (Pascher, 1976). The configuration of the two hydrophobic chains is represented in a 'fluid' state with three rotational isomers of a '2g1 kink' type (cf. Trauble & Haynes, 1971; Seelig & Seelig, 1974) according to the liquid-expanded character of the ganglioside interfaces (Maggio *et al.*, 1978a). In this configuration, the chains can be more disordered while remaining parallel to each other and still maintain a long-range order (Seelig & Seelig, 1974). For the oligosaccharide chain the pyranose rings of the carbohydrate units are represented in chair form and the configuration (α or β) of the glycosidic linkage is preserved. With these constraints the oligosaccharide backbone adopts a position approximately perpendicular to the interface, in agreement with monolayer studies at high surface pressures (Maggio *et al.*, 1978a). Due to the conformation of this backbone the α -linked sialosyl groups adopt a position in which the carboxylate group is oriented differently in each of these residues. The carboxylate group of AcNeu₁ is above the plane of the sialosyl moiety and oriented towards the interface. Conversely, the carboxylate group in AcNeu₂ and AcNeu₃ is below its respective sialosyl plane and oriented away from the interface. Since these groups carry a negative charge at pH 5.6 and therefore represent the negative ends of the sialosyl dipole-moment vectors, their different orientation will determine the direction of this vector in monolayers and this will be abolished under protonation (Maggio *et al.*, 1978a).

The position of a sialosyl residue in the polar head group of the gangliosides can affect its interaction with Ca²⁺. It is known that Ca²⁺ can interact with either free sialic acid or ganglioside G_{M1}, forming co-ordination complexes in which the glycerol side chain of sialic acid (C₇, C₈ and C₉) is involved and that colominic acid, a polymer of sialic acid linked through the glycerol chain, does not show interactions with the cation (Jaques *et al.*, 1977; Sillerud *et al.*, 1978). The small interaction with Ca²⁺ of sialosyl-sialosyl linked sialic acid in gangliosides G_{T1} and G_{D3} (Fig. 1c) is probably due to the involvement of the glycerol chain in this linkage thus failing to form a complex efficiently with the cation. Whether the differences in the interaction with Ca²⁺ exhibited by AcNeu₂ and AcNeu₁ in ganglioside G_{D1a} or AcNeu₁ in ganglioside

EXPLANATION OF PLATE 1

Molecular models of trisialoganglioside and dipalmitoyl phosphatidylcholine

Space-filling Corey–Pauling–Koltun molecular models illustrating some possible configurations and molecular interactions of ganglioside G_{T1} and dipalmitoyl phosphatidylcholine. Outline projections of the models are also shown to illustrate relevant moieties and interactions. The molecules are considered to be in a closely packed state (i.e. above a surface pressure of $30 \text{ mN} \cdot \text{m}^{-1}$). The position of the air/water interface should be taken as an example only. An equimolar mixture of ganglioside G_{T1} and dipalmitoyl phosphatidylcholine exhibiting non-interacting behaviour is shown in (a); (b) shows a possible arrangement showing intermolecular interactions. In (a) the phospholipid is represented with the acyl chains in all-*trans*-configuration and its polar head group in an average position according to the work of Phillips *et al.* (1972) and Gally *et al.* (1975). For ganglioside G_{T1}, the configuration of the ceramide moiety is represented essentially according to the work of Pascher (1976) and with three co-operative rotational isomers of the type '2g1 kink' (Trauble & Haynes, 1971; Seelig & Seelig, 1974) in each hydrophobic chain. The position of the oligosaccharide chain is represented as deduced from monolayer studies (Maggio *et al.* 1978a). The vectors in the outline projections represent dipole-moment contributions (positive towards the arrow; cf. Gaines, 1966). In (b) the phospholipid acyl chains are represented exhibiting rotational isomers occurring co-operatively with those of ganglioside G_{T1} so that the phosphocholine moiety fits in the 'pocket' circumscribed by AcNeu₃, with the quaternary nitrogen atom pointing towards the observer. Broken lines joining particular groups in the outline projections represent possible electrostatic interactions between corresponding charged groups (see the text). AcNeu₁ represents the sialosyl residue attached to the galactose proximal to the ceramide moiety; AcNeu₂ represents the sialosyl residue bound to the terminal galactose of the tetrasaccharide chain; AcNeu₃ represents the sialosyl residue in sialosyl-sialosyl linkage (see abbreviations used).

G_{M1} is due to the different dipolar properties of these residues (Maggio *et al.*, 1978a), to the different position that the bivalent cation may adopt with respect to anionic groups (Shah, 1970) or to a different proximity to the interface of the sialosyl residues interacting with Ca^{2+} thus affecting the sensitivity of the surface-potential changes cannot be concluded from the present experiments.

From previous studies (Maggio *et al.*, 1978b) it was clear that the dipolar properties of AcNeu₂ or AcNeu₃ in polysialogangliosides were essential to establish particular interactions with phosphatidylcholine. These interactions were independent of the type of hydrophobic chains of the phospholipid, but the presence of a phosphocholine moiety in its polar head group appeared to be a requirement for a decrease in molecular packing and surface potential with polysialogangliosides. Phospholipids containing other polar head groups did not show the same behaviour.

An illustration of a possible interaction between ganglioside G_{T1} and phosphatidylcholine in mixed monolayers is shown in Plate 1(b). In this arrangement the negative end of the dipole-moment vector of the zwitterion of the phospholipid, which is the anionic phosphate (Shah & Shulman, 1965), is represented, establishing ion-dipole interactions with the glycerol chain of AcNeu₃. It has previously been reported that the anionic oxygen atom of phospholipids can participate in interactions of this type with hydroxy groups of glycerol-containing polar head groups of other lipids (Maggio & Lucy, 1976). The positively charged trimethylammonium group of the phosphocholine moiety (the positive end of the zwitterion dipole; Shah & Shulman, 1965) could thus remain at a distance from the anionic carboxylate group (negative end of the sialosyl dipole; Maggio *et al.*, 1978a) of either AcNeu₁ or AcNeu₃, which may allow electrostatic interactions (Chapman, 1969). This type of arrangement could explain decreases in surface potential with respect to a non-interacting state, since it would correspond to a partial matching and neutralization of two oppositely oriented electrical vectors contributed by the zwitterionic phosphocholine and AcNeu₃ respectively. The arrangement can also account for a decrease in molecular packing (Maggio *et al.*, 1978b) through a 'molecular cavity' effect (see Plate 1a; cf. Shah, 1970; Maggio & Lucy, 1975, 1976). A similar configuration (not shown) with phosphatidylcholine can be obtained with disialogangliosides G_{D3} and G_{D1a} through the participation of their sialosyl residues that bear a dipole-moment vector oriented as AcNeu₃ (Maggio *et al.*, 1978a), but not with monosialogangliosides whose single sialosyl residue (AcNeu₁) has a dipole-moment vector oriented in the same direction as that of the phospholipid zwitterion (see Plate 1a). This and the

fact that the anionic carboxylate group of AcNeu₁ in monosialogangliosides and the anionic oxygen atom of the phosphate group of phosphatidylcholine lie at approximately the same distance from the interface would establish electrostatic repulsions with monosialogangliosides that can explain monolayer expansions (Maggio *et al.*, 1978b). With polysialogangliosides this effect may be overcome by a more favoured ion-dipole interaction of the anionic phosphate of the phospholipid with the glycerol chain of AcNeu₂ or AcNeu₃ directed towards the interface. As in other cases (Maggio *et al.*, 1977), these interactions must be seen as average molecular arrangements among several possibilities and occurring dynamically with the concomitant participation of more than two molecules, since the orientation of the polar head groups either in gangliosides (Maggio *et al.*, 1978a) or phosphatidylcholine (Gally *et al.*, 1975) is not fixed but represents only the more probable average position. In addition, the energetics of the system reveal that these interactions are not occurring permanently between these molecules and the interface corresponds to a non-localized state (B. Maggio, F. A. Cumar & R. Caputto, unpublished work).

The experiments with dihexadecyl phosphate and hexadecyltrimethylammonium indicate that to obtain the type of interactions between phosphatidylcholine and polysialogangliosides the interface should contain both charged groups of the phosphocholine moiety, but these need not necessarily be present on the same molecule. Di- and tri-sialogangliosides are able to induce membrane fusion in chicken erythrocytes and stimulate the release and inhibit the uptake of neurotransmitter in nerve endings (Maggio *et al.*, 1978c; Cumar *et al.*, 1978, 1980). These effects on natural membranes are also exhibited by other fusogenic lipids that, similarly to polysialogangliosides, show decreases in molecular packing and surface potential in mixed monolayers with phosphatidylcholine. These interactions also require the presence of a phosphocholine moiety with a positively charged trimethylammonium group and a negative charge on the phosphate (Maggio & Lucy, 1976). However, for fusogenic lipids such as mono-oleoylglycerol, those two charged groups must be present on the same phospholipid molecule, since the interactions are not the same if phosphatidylcholine is replaced by an equimolar mixture of dihexadecyl phosphate and hexadecyltrimethylammonium. This is consistent with the finding that the polar head group on this type of fusogenic lipid does not influence the interactions with phospholipids, but a requirement in this type of fusogenic lipid is the presence of a low-melting chain that may favour, via the hydrophobic region, intra- or inter-molecular polar-head interactions between charged groups of individual or adjacent phos-

pholipid molecules (Maggio & Lucy, 1976). With polysialogangliosides, the situation is different; the requirements are related to the presence of particular dipolar components in the oligosaccharide chain of the ganglioside and of charged groups in the phospholipid. The establishment of the characteristic polar-head-group interactions that will decrease the surface potential in this case occurs via the polar region not requiring the presence of the groups involved on the same specific molecule.

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References

- Bangham, A. D. (1968) *Prog. Biophys. Mol. Biol.* **18**, 29–95
- Chapman, D. (1969) in *Structural and Functional Aspects of Lipoproteins in Living Systems* (Tria, E. & Scanu, A. M., eds.), pp. 3–36, Academic Press, London and New York
- Cumar, F. A., Maggio, B. & Caputto, R. (1978) *Biochem. Biophys. Res. Commun.* **84**, 65–69
- Cumar, F. A., Maggio, B. & Caputto, R. (1980) *Biochim. Biophys. Acta* **597**, 174–182
- Gaines, G. L. (1966) in *Interscience Monographs on Physical Chemistry: Insoluble Monolayers at Liquid-Gas Interfaces* (Prigogine, I., ed.), pp. 281–300, Interscience, New York
- Gally, H. U., Niederberger, W. & Seelig, J. (1975) *Biochemistry* **14**, 3647–3652
- Jaques, L. W., Brown, E. B., Barret, J. M., Wallace, S. B., Jr. & Weltner, W., Jr. (1977) *J. Biol. Chem.* **252**, 4533–4538
- Maggio, B. & Lucy, J. A. (1975) *Biochem. J.* **149**, 597–608
- Maggio, B. & Lucy, J. A. (1976) *Biochem. J.* **155**, 353–364
- Maggio, B., Diplock, T. A. & Lucy, J. A. (1977) *Biochem. J.* **161**, 111–121
- Maggio, B., Cumar, F. A. & Caputto, R. (1978a) *Biochem. J.* **171**, 559–565
- Maggio, B., Cumar, F. A. & Caputto, R. (1978b) *Biochem. J.* **175**, 1113–1118
- Maggio, B., Cumar, F. A. & Caputto, R. (1978c) *FEBS Lett.* **90**, 149–152
- Pascher, I. (1976) *Biochim. Biophys. Acta* **455**, 433–451
- Phillips, M. C., Finer, E. G. & Hauser, H. (1972) *Biochim. Biophys. Acta* **290**, 397–402
- Seelig, A. & Seelig, J. (1974) *Biochemistry* **13**, 4839–4845
- Shah, D. O. (1970) *Adv. Lipid Res.* **8**, 347–431
- Shah, D. O. & Shulman, J. H. (1965) *J. Lipid Res.* **6**, 341–349
- Sillerud, L. O., Prestegard, J. H., Yu, R. K., Schafer, D. & Konisberg, H. (1978) *Biochemistry* **17**, 2619–2627
- Svennerholm, L. (1963) *J. Neurochem.* **10**, 613–623
- Trauble, H. & Haynes, D. H. (1971) *Chem. Phys. Lipids* **7**, 324–335