Colloid Polym Sci 273:687–692 (1995)

ORIGINAL CONTRIBUTION

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# Adsorption of codeine on hydrophilic silica and silica surface modified by hydrophobic groups in the presence of electrolytes

Received: 28 November 1994
Accepted: 30 January 1995

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**Abstract** The adsorption of codeine from aqueous solution onto colloidal silica and silica surface-modified with chemiadsorbed octadecyl dimethyl silane (ODDMS) or dimethyl silane (DMS) groups was studied in the presence of neutral electrolytes at different pH values. From codeine-hydrochloride solutions codeine cations are strongly bound to negatively charged silica surfaces. Inorganic salts (NaCl, $NaNO_3$) reduce the adsorption of the organic cation. On silica modified by ODDMS (10% of surface silanol groups are occupied), codeine cations are adsorbed to a higher extent at pH 6, while at pH 8 the adsorbed amounts are lower than on the bare silica surface. Neutral electrolytes reduce codeine adsorption on the ODDMS modified silica. On the hydrophobic silica, completely covered by DMS groups, codeine adsorption is considerably lower than on the bare silica, but neutral salts increase the adsorption. The adsorption of codeine is compared with the adsorption of aggregating surfactant ions. Common and different features of their interactions with silica surfaces are outlined.

**Key words** Adsorption – codeine – surface modified – silica – alkyl group – electrolyte – pH

## Introduction

The adsorption of organic cations to silica surfaces from aqueous solution is mainly due to electrostatic interactions with negatively charged adsorption sites [1]. Aggregating organic cations, the cationic surfactants, often show an S-shaped adsorption isotherm on silica, representing a two-step interaction [2–4]. The first step is due to the electrostatic interactions, mentioned above. The second step, beginning near the region of the critical micelle concentration (CMC) of the surfactant, is attributed to surface aggregation, forming surface micelles [5, 6]. In these adsorbates the primarily (electrostatically) adsorbed species serve as anchors for the aggregation of further surfactant ions, which are accompanied by their counterions.

Neutral electrolytes such as sodium chloride reduce the adsorption of surfactant cations in the initial step. In the second step they significantly increase surface aggregation [7, 8]. Surface aggregation of surfactants, further improved by electrolytes is also observed on alkyl chains of octadecyl dimethyl silane (ODDMS) residues which are chemiadsorbed onto silica [9]. These alkyl chains serve as anchors for surfactant adsorption by surface aggregation.

A clear distinction between the opposite effects of neutral electrolytes – reduction of primarily adsorbed surfactant ions at low surfactant concentration and improving surface aggregation at higher concentration of the surfactant – is not easy to evaluate. With increasing electrolyte concentration the CMC of the surfactants shifts towards lower concentrations. As a consequence, the second step of the adsorption isotherm increasingly superimposes the first step [8].

To get a better picture of these surface reactions and to elucidate the role of hydrophobic surface groups, the adsorption of a nonaggregating organic cation, codeine [4,5α-epoxy-3 methoxy-17 methyl-7-morphinen- 6α-ol], was studied on bare and surface-modified silica. Like other alkaloids and amines, codeine is strongly adsorbed by bare silica from aqueous solution by ion exchange and from nonpolar liquids by hydrogen bonds [10–12].

In this paper the influence of hydrophobic surface groups on silica on codeine adsorption from aqueous solution is studied in the presence of neutral electrolytes and at different pH values. The adsorption is discussed by comparison with the adsorption of surfactant ions under the same conditions.

## Experimental

### Materials

Codeine-HCl, according to Pharm. Eur. II; NaCl, NaOH, $NaNO_3$, all analytical grade (E. Merck, D-Darmstadt). Silicas: Aerosil Ox50, BET surface ($N_2$) 52 $m^2 g^{-1}$, Aerosil R 972, surface methylated, BET surface ($N_2$) 124 $m^2 g^{-1}$ (Degussa, D-Frankfurt a.M.), surface modified silica, source Aerosil Ox50, was obtained by chemisorption of octadecyl dimethyl methoxy silane (Wacker Chemie, D-Burghausen) as described elsewhere [13]; content of organic residues 0.3 $\mu mol\, m^{-2}$.

The adsorption of codeine including control of pH was determined after establishment of adsorption equilibria from the codeine concentration in the supernatant liquid of silica dispersions [14].

## Results and discussion

### Adsorption on bare silica

The adsorption of codeine to bare silica is contrasted in Figs. 1–3 at different pH values and in the presence of different amounts of sodium chloride. At pH 2 the adsorption of codeine cations remains small with a saturation value of 0.1 $\mu mol\, m^{-2}$ according to the low surface charge of silica (Fig. 1) [15]. Sodium chloride added to the adsorption system shows the tendency to reduce codeine adsorption.

At pH 6.5 codeine adsorption to bare silica is enhanced according to the increase of negative surface charges (Fig. 2). The adsorption isotherm of codeine cations[1] corresponds to the initial part of the adsorption isotherm of surfactant ions at the same pH. Also, the saturation value of adsorption of 0.95 $\mu mol\, m^{-2}$ (Table 1) is in the range of the first plateau of surfactant adsorption far below the

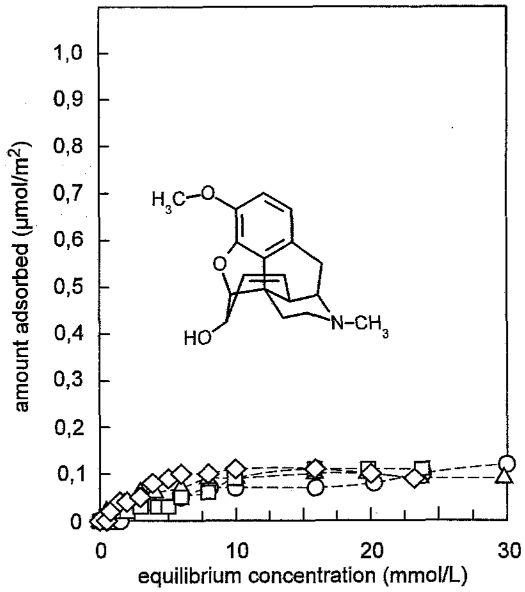

**Fig. 1** Adsorption of codeine-hydrochloride on Aerosil Ox 50 at pH 2 in the presence of sodium chloride ○ without Nacl; △ 0.001 M NaCl; □ 0.1 M Nacl; ◇ 0.1 M Nacl

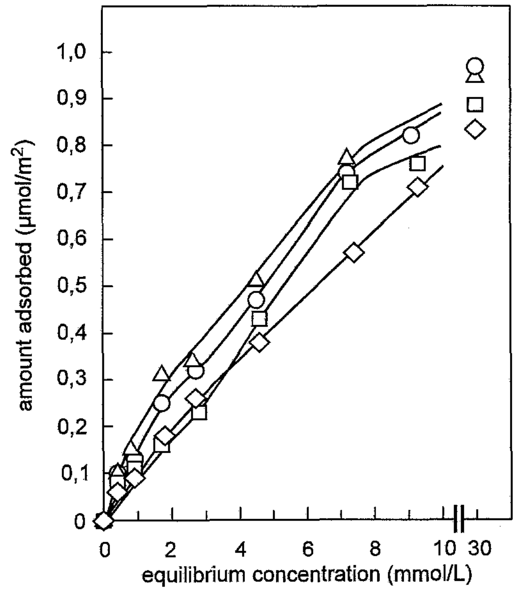

**Fig. 2** Adsorption of codeine-hydrochloride on Aerosil Ox 50 at pH 6.5 in the presence of sodium chloride ○ without additives/with 0.1 M urea; △ 0.01 M NaCl; □ 0.1 M Nacl; ◇ 0.5 M NaCl

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[1] At pH 6.5 90% of codeine is present as cations; $pK_b = 6.1$ [16]

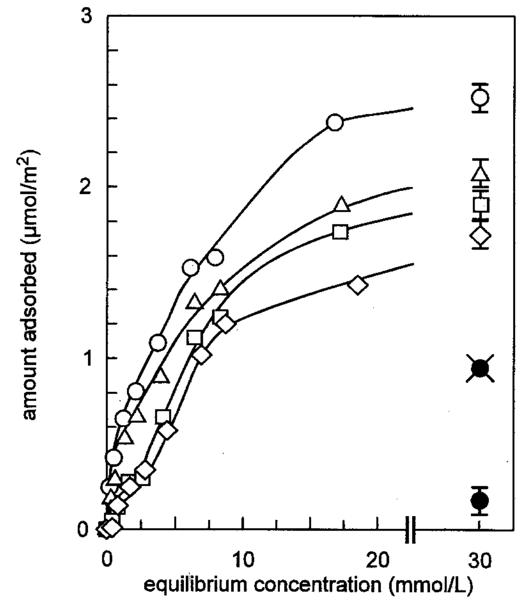

**Fig. 3** Adsorption of codeine-hydrochloride on Aerosil Ox50 at pH 8 in the presence of sodium chloride ○ without NaCl; △ 0.01 M NaCl; □ 0.1 M NaCl; ◇ 0.5 M NaCl; ● saturation at pH 2 without NaCl; ✱ Saturation at pH 6.5 without NaCl

CMC [17, 18]. At pH 8 (Fig. 3) the plateau value of codeine adsorption is further increased to 2.5 $\mu$mol m$^{-2}$ indicating that more than 60% of the total available silanol groups are occupied by codeine [19].

Sodium chloride reduces the codeine adsorption on bare silica. This effect is more pronounced at pH 8 where codeine adsorption is reduced to less than 70% in the presence of 0.5 M NaCl than at pH 6.5 where the codeine adsorption is only reduced to 87% by the same amount of NaCl. These examples demonstrate the stronger binding of codeine to silica in comparison to sodium ions. Only 15-30% of codeine is displaced from the surface by a NaCl concentration 25 times higher than the equilibrium concentration of codeine. The weak displacing action of sodium chloride on codeine clearly shows that, apart from electrostatic interactions, additional adsorption forces between the surface and organic cations and differences in hydration between inorganic and organic cation contribute to the total interactions at the surface.

Hydrogen bonds between codeine molecules and silica, which are responsible for strong binding from nonpolar liquids [12], may be of minor importance for adsorption from aqueous solution [10, 20]. In the case of surfactant ions it is assumed that hydrophobic interactions between the hydrocarbon chains and nonpolar patches of the surface may contribute to the strong adsorption [21]. Even in the case that such nonpolar regions would exist between the strongly hydrated silanol groups on silica, it seems rather unlikely that the small, compact codeine cations, located on the charged silanol sites can additionally establish any interactions with such hydrophobic patches. In addition, if there are hydrophobic surface sites in the range of a hydrocarbon tail size on a polar silica surface, then their effect on interaction with an adsorptive should become smaller at high pH values where the surface is fully hydrated by the polar dissociated silanol groups. The stronger binding of organic cations on hydrophilic silica with increasing pH contradicts this view of interactions with "a priori" hydrophobic adsorption sites.

**Table 1** Saturation values of adsorption of organic cations on silica and surface-modified silica$^{+}$

| Adsorptive: | | Codeine | | | | | | Tetradecylpyridinium$^{++}$ | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Counterion: | | -hydrochloride | | | | | -nitrate | -chloride | | -nitrate | |
| Additive: | | None | 0.01 M NaCl | 0.1 M NaCl | 0.5 M NaCl | Urea | NaNO$_3$ 0/0.1 M | None | 0.1 M NaCl | None | 1 M NaNO$_3$ |
| Absorbent: | pH 2 | 0.1 | 0.1 | 0.1 | – | – | – | | | | |
| Bare silica<br>Aerosil Ox 50 | pH 6.5 | 0.95 | 0.95 | 0.9 | – | 0.95 | 0.4/0.9 | 1.2 | 3.6 | 5.5 | 6.5 1) |
| | pH 8 | 2.5 | 2.1 | 1.9 | 1.7 | – | – | | | | |
| Octadecyldimethylsilane modified silica | pH 6.5 | 1.5 | | 1.3 | 1.1 | – | – | 1.7 | – | – | – |
| | pH 8 | 1.9 | | 1.85 | 1.7 | – | – | | | | |
| Methylated silica<br>Aerosil R 972 | pH 4 | 0.15 | 0.25 | 0.8 | – | – | – | 2.8 2) | 4.0 2) | 2.1 2) | – |

$^{+}$ The values are derived from plateau regions of adsorption isotherms. Equilibrium concentration range > 5 mmol/L
$^{++}$ pH at equilibrium 3.5–4.5
1) Diss. J. Sigg, p. 131 [18] 2) Rupprecht H. [8]

Although there are great differences in the molecular structure between the nonaggregating codeine and surfactant ions such as tetradecylpyridinium cations, their adsorption behavior on silica from aqueous solution shows some common features. We suppose, therefore, that v.d. Waal interactions between the intimate surrounding of charged adsorption sites on the surface and nonpolar parts of organic cations are responsible for additional adsorption forces. After charge compensation between a surface site and an organic cation the area of contact in the corresponding adsorbate is left nonpolar. Primarily adsorbed water of hydration on the involved charged groups can easily be displaced after charge compensation. This mechanism should not be sensitive to changes in water structure. Obviously, this is the case, because urea, a water-structure-breaking substance, shows no influence on the adsorption of codeine at pH 6.5 (Fig. 2).

The differences in the adsorption of codeine and surfactant ions at higher equilibrium concentrations of the adsorptive (near the CMC) are due to the surface aggregation of surfactant ions. This aggregation during the second step of adsorption isotherm is increased by neutral salts and depends strongly on the kind of counterion [7–9, 22]. For example, the saturation value of the adsorption of tetradecylpyridinium nitrate is three times higher than that of the corresponding chloride salt, due to different influences on charge compensation of the polar headgroups [8, 23] (Table 1). In contrast to the stimulating action on surfactant adsorption, nitrate ions displace codeine more effectively than chloride from silica, as shown by the adsorption isotherms of codeine in the presence of equivalent amounts of sodium chloride and sodium nitrate respectively (Fig. 4, Table 1). Probably, the hydration near the surface is differently influenced by these inorganic anions.

## Adsorption on surface modified silica

For a further comparison of the adsorption behavior of codeine and surfactant ions a silica, surface modified by chemiadsorbed ODDM groups, was used as adsorbent. These groups show an equivalent anchor function in the surface aggregation process of surfactants, both on silica and titanium dioxide. The saturation values of surfactants ions are, therefore increased with the number of these surface groups [6, 9] (Table 1).

At pH 6.5 the adsorption of codeine is also significantly increased (Fig. 5, Table 1). The saturation value of 1.5 $\mu$mol m$^{-2}$ is about 40% higher than on the bare silica. At pH 8, however, an opposite effect on codeine adsorption is obtained by the ODDMS groups (Fig. 6). Compared with the saturation value of adsorption on bare silica with 2.5 $\mu$mol m$^{-2}$ only 1.9 $\mu$mol m$^{-2}$ are obtained on the surface modified adsorbent. Sodium chloride reduces codeine adsorption to the same extent on the ODDMS group modified silica as on the bare silica at pH 6.5, while at pH 8 the reducing action of the inorganic salt is considerably smaller.

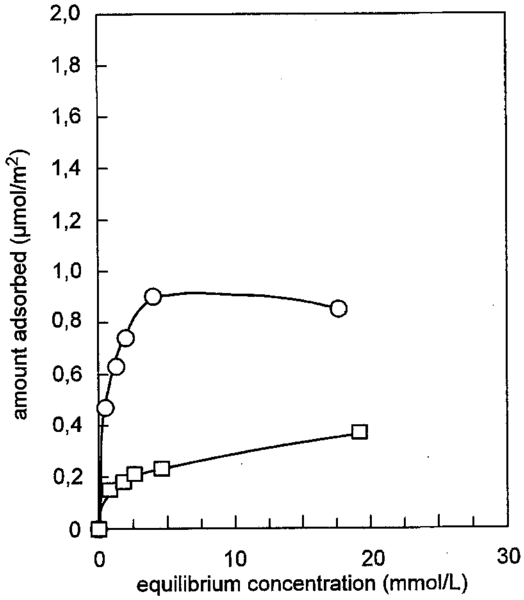

**Fig. 4** Adsorption of codeine-nitrate on Aerosil Ox 50 at pH 8 in the presence of sodium nitrate. ○ without salt; □ 0.1 mol/L sodium nitrate

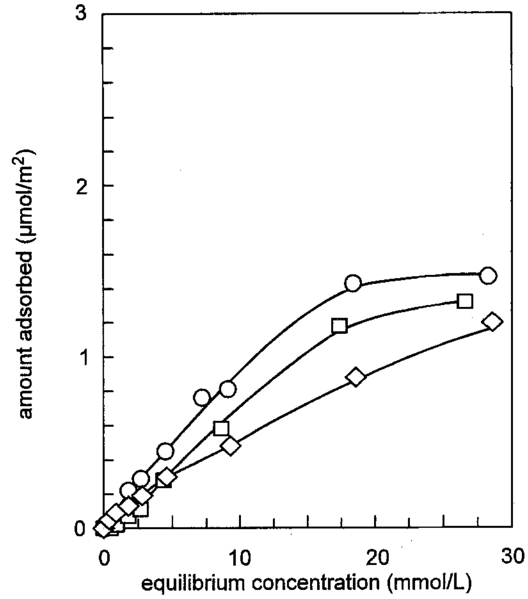

**Fig. 5** Adsorption of codeine-hydrochloride on Aerosil Ox 50 with 0.3 $\mu$mol/m$^2$ chemiadsorbed ODDM groups at pH 6.5 in the presence of sodium chloride ○ without NaCl; □ 0.1 mol/L NaCl; ◇ 0.5 mol/L NaCl

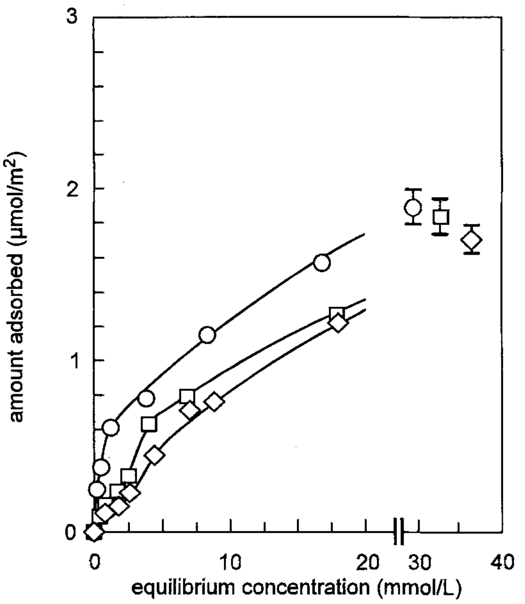

**Fig. 6** Adsorption of codeine-hydrochloride on Aerosil Ox 50 with 0.3 $\mu$mol/m$^2$ chemiadsorbed ODDM groups at pH 8 in the presence of sodium chloride ○ without NaCl; □ 0.1 mol/L NaCl; ◇ 0.5 mol/L NaCl

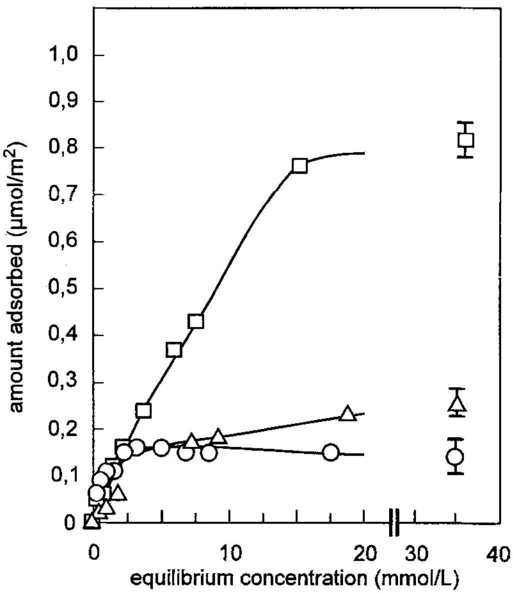

**Fig. 7** Adsorption of codeine-hydrochloride on Aerosil R 972 at pH 6.5 in the presence of sodium chloride ○ without NaCl; △ 0.05 mol/L NaCl; □ 0.1 mol/L NaCl

The ODDMS groups obviously enhance the adsorption forces between codeine and silica without serving as independent adsorption sites (anchors) as in the case of surfactant ions. In the neighborhood of charged adsorption sites they may contribute to stronger nonpolar interactions. The decrease of adsorption at pH 8 on the ODDMS group modified silica is due to the fact that the density of silanol groups is reduced by the chemiadsorbed organic species by about 15%. This reduction of available silanol groups comes into play at high pH values, when most of the silanol groups are negatively charged [24]. At lower pH values a sufficient number of silanol groups is still available even on the modified silica to establish the corresponding surface charge [25]. The weaker reducing action of sodium chloride on the surface modified silica at pH 8 supports the view of stronger binding of codeine cations (or molecules), if nonpolar residues are available for additional interactions in the vicinity of charged groups.

On the adsorbent Aerosil R 972 most of the silanol groups ( $>$ 80%) are substituted by dimethylsilane groups, leaving the surface completely hydrophobic [26]. At pH 6.5 a saturation value of codeine adsorption of 0.15 $\mu$mol m$^{-2}$ is obtained, only 12% of the adsorption to the bare silica surface. In the presence of 0.1 M NaCl the codeine adsorption is considerably increased to 0.8 $\mu$mol m$^{-2}$ exceeding even the adsorption to bare silica under the same conditions.

In the presence of neutral salts the codeine adsorption to the hydrophobic adsorbent shows the same tendency to increase as it is observed during surface aggregation, i.e. adsorption of surfactant ions. However, the formation of surfactant-like aggregates of codeine can be ruled out. The increased amount of codeine cations results from the reduction of their mutual electrostatic interaction with increasing electrolyte concentration [27].

## Summary

The adsorption of nonaggregating codeine and aggregating surfactant cations shows common but also different features. The negatively charged silica surface adsorbs the organic cation according to the number of available adsorption sites, capable for ion exchange. The amount of adsorbed codeine increases with increasing pH and is reduced at a given pH by neutral electrolytes.

This is obviously due to a concurrency between codeine cations and cations of the added electrolyte such as sodium at the adsorption sites. However, a considerable surplus of inorganic cations is necessary to replace codeine significantly. Hydrophobic groups on silica strengthen nonpolar adsorption forces, but reduce the number of negatively charged adsorption sites.

At higher concentrations the adsorption of codeine is different from that of surfactants which aggregate on the

surface. It is the self aggregating behavior of surfactant ions which widely determines the adsorption to the silica surface, independent of small differences in their molecular structure (i.e., kind of polar headgroup, hydrocarbon chain structure).

On hydrophobic silica both codeine and surfactant ions are predominantly bound by nonpolar forces to the surface. Mutual interactions between hydrocarbon chains contribute to the obviously higher adsorption values of the surfactant ions compared with codeine.

Neutral electrolytes also increase the adsorption of codeine on silica with nonpolar groups, due to a reduction of mutual repulsion between charged groups of the adsorptive. The considerably high amount of codeine adsorption on the methylated silica R 972 in the presence of sodium chloride appears like a salting-out effect. We assume that in addition to the electrostatic effect the water structure enhancing action of NaCl may support hydrophobic interactions between the organic cations and the methylated surface.

**Acknowledgement** The support of the following was greatly appreciated: DEGUSSA, Frankfurt a M.; the Fond der Chemie, Frankfurt; E. Merck, Darmstadt; Wacker Chemie, Burghausen. We thank Dr. Jiri Strnad for his fruitful and stimulating discussions.

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