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Assembled nanoparticle films with crown ether–metal ion ''sandwiches'' as sensing mechanisms for metal ions

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Abstract Specialized nanoparticles known as monolayer-protected clusters (MPCs) were affixed with metal selective crown ether (CE) functional groups and assembled into novel thin films to form potential metal ion sensing materials. Films of MPCs modified with potassium specific 15-crown-5 ligands (CE-MPCs) were successfully assembled using both dithiol linkages and ester-coupling reactions. Film responses to potassium are observed spectroscopically as the manifestation of changing interparticle spacing within a film in the presence and absence of potassium. Growth dynamics, film structure, and metal response are examined. Additionally, the important role of flexibility, especially in the interconnectivity of the CE-MPCs within the film and between the CE groups themselves, is experimentally identified.

Introduction

Specialized materials capable of detecting metal ions in solution with adequate selectivity and sensitivity are of interest for a variety of medical, bioanalytical, and environmental-based applications [1]. For effective detection and quantification of metal ions, the sensing material should be able to detect a specific metal ion, even at low concentration and within a complex matrix. The most ideal materials would be portable, easily used without extensive laboratory equipment, reusable or disposable in a cost-effective manner, and have the potential for miniaturization for the purposes of innovative, hand-held devices and possible development of in vivo applications [2].

Over the past decade, the emergence and continuing development of nanotechnology has introduced several unique materials that may be advantageous for these metal sensing applications [3, 4], including metallic nanoparticles [5]. A specific type of nanoparticle, referred to as a monolayer protected cluster (MPC), possesses a small metal core several nanometers in diameter and a peripheral layer of alkanethiols that stabilize and prevent aggregation of the particles to bulk material. Aside from this enhanced stability, MPCs are particularly attractive as potential metal sensing materials because their properties can be readily manipulated by altering the core size and the functionality of the peripheral ligands [6]. The modification of these nanoparticles through exchange reactions [7] with specific functionalized ligands, namely *ω*-substituted-*n*-alkanethiols, allows for MPCs to be assembled into film geometries [8] and/or be affixed with metal ion selective moieties [9, 10].

The use of functionalized MPCs as a sensing material for metal ions has been investigated by Hupp et al. [11], who showed that carboxylic acid modified MPCs can be used to detect low concentrations of environmentally relevant heavy metal ions (e.g., Pb^{2+}, Hg^{2+}, or Cd^{2+}) with a solution aggregation mechanism that yields a colorimetric and reversible response. The carboxylic acid MPC solution changed from red to blue as metal ions became coordinated between acid groups of adjacent

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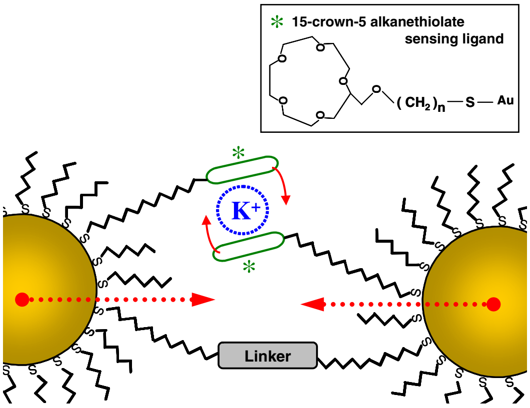
nanoparticles and induced aggregation. This response to metal ions was monitored spectroscopically by observing a distinctive shift toward higher wavelengths (i.e., a red shift) of the signature surface plasmon band (SPB) signal from the MPC in solution as the metal-induced aggregation occurs. A corresponding blue shift was observed with the removal of the heavy metals via EDTA titration. The SPB is a small absorbance peak in the spectra of these solutions or thin films of MPCs and represents a collective response of the surface conduction electrons in the material to the electric field imposed by some incident electromagnetic radiation [12]. More importantly, the position and magnitude of the SPB is known to be sensitive to the local molecular environment including solvent interactions, dielectric, and, in this case, interparticle spacing (aggregated versus non-aggregated solutions) [13, 14]. Hupp focused on the sensitivity toward certain metal ions but did not specifically address a lack of selectivity in the system, as all the metals tested were coordinated in the same manner and to the same extent.

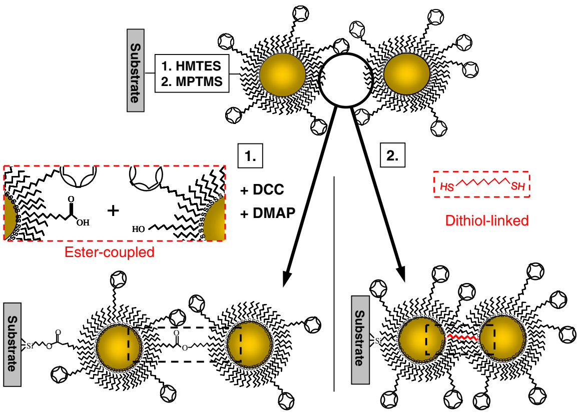
In an effort to increase the selectivity of these solutions systems, Chen [9, 15, 16] integrated ionophores, namely crown-ether terminated *n*-alkanethiols, on the MPCs to create materials able to respond to potassium ions in solution. Potassium is an analyte of interest because of its important role in many physiological functions, causing its measurement in blood and urine to be a vital diagnostic tool for disorders. Current clinical measurement of potassium is done in a laboratory using potentiometry and ion selective electrodes, which is both time consuming and susceptible to electrode fouling. Thus, there is an interest in the development of a material that could potentially be used to make potassium measurements more efficient and localized to the vicinity of the patient.

Crown ether molecules are ring-like structures with cavities that will coordinate only specific metal ions [17]. By modifying MPCs with 15-crown-5 alkanethiols, Chen created solutions of crown-ether modified MPCs (CE-MPCs) that exhibited a selective colorimetric response toward potassium ions. The 15-crown-5 ring structure is normally able to specifically coordinate with a single sodium ion. However, as Chen observed, with the introduction of potassium into a solution of these CE-MPCs, 15-crown-5 groups from different MPCs are able to ‘‘sandwich’’ a single potassium ion (Scheme 1). Similar to Hupp's system, these CE–metal–CE ‘‘sandwiches’’ cause the solution MPCs to aggregate in the presence of a specific metal ion, bringing cores into closer proximity and subsequently altering their optical properties (i.e., the solution changes from red in the presence of Na^+ ions to blue in the presence of K^+ ions and showed a corresponding spectroscopic red shift). The ‘‘sandwich’’ interaction is strong and has been explored by Chen and others as a metal coordinated linking mechanism between MPCs [9, 10, 15, 16]. Chen's system shows a more selective response toward metal ions but has the unfortunate disadvantage of irreversible aggregation to the point of eventual precipitation of CE-MPCs [15], limiting the potential for this technology to be implemented as part of an in-vivo metal ion detector.



Scheme 1 MPC film linking and CE–metal ion–CE ‘‘sandwich’’ sensing mechanisms

In this study, we seek a similar response to metal ions from films of MPCs incorporating CE moieties. The film geometry offers many advantages for the aforementioned sensing applications, rendering precipitation a non-issue and offering the potential for use in remote sensing devices that utilize arrays capable of high throughput screening of samples [18]. Certain MPC films, without CE modification, have been studied extensively as chemiresistive sensors and found to be extremely flexible materials [19–26]. These films are known to swell in the presence of certain solvents, causing changes in the film's conductivity, mass, and SPB in response to the corresponding increase in core-to-core spacing [25]. Thus, the SPB can be used as a diagnostic of interparticle spacing within nanoparticle solutions and films; red and blue shifts serving as indicators for smaller or larger interparticle distances, respectively [13]. If ionophores such as CEs are incorporated into the MPC film, it is conceivable that their ability to sandwich metal ions may instigate significant movement of the MPCs cores even within a film architecture [27]. That being stated, film structures are severely constrained compared to solution systems so the response to metal ions is expected to be much more subtle. This paper seeks to explore the feasibility of using CE-MPC films as selective, metal ion sensitive materials. Growth dynamics and response to metal ion stimuli of two types of assemblies, dithiol-linked and ester-coupled films (Scheme 2), were investigated in an attempt to achieve these specific characteristics.



Scheme 2 Synthesis of ester-coupled versus dithiol-linked MPC films

Experimental

Unless otherwise stated, all materials were available commercially from Sigma/Aldrich. Procedures for synthesizing different-sized hexanethiolate-protected MPCs and modifying their peripheral layer via simple place-exchange reactions have been described in detail elsewhere [7, 28]. Briefly, aqueous solutions of gold salt ($HAuCl_4$) were phase-exchanged into toluene with tetraoctyl ammonium bromide. Hexanethiol (C6) was then added to the organic layer in varying amounts to influence core size. Finally, after cooling to 0 °C, the slurry was reduced with the addition of sodium borohydride, producing a black precipitate that was collected, washed and characterized. Using either 3:1 or 2:1 thiol-to-gold ratios in the synthesis, two general sizes of MPCs were produced. The *average* composition of the synthesized cores was $Au_{140}(C6)_{53}$ and $Au_{220}(C6)_{75}$ gold atoms, Au140-MPC and Au220-MPC, respectively. Functionalization of the MPCs was then achieved via well-known place exchange reactions [28] where the nanoparticles and ligand(s) to be inserted into their alkanethiolate periphery are co-dissolved in a solvent and stirred. Over time, ligands in solution are exchanged with ligands attached to the MPC, effectively functionalizing the periphery of the MPC. Incorporation of the ω-substituted-n-alkanethiols, including 15-crown-5-n-alkanethiols (synthesized as previously described [10]), 11-mercaptoundecanoic acid (MUA), 11-mercaptoundecanol (MUD), and 6-mercaptohexanol (MHOL), was verified via NMR after iodine decomposition treatment as previously shown [25, 26]. Place-exchange reactions were carried out simultaneously in dichloromethane and the results verified with NMR as shown in Fig. 1 after the material had undergone oxidative decomposition with iodine treatment. Typical compositions for CE single exchange systems of Au140-MPC and Au220-MPC were $Au_{140}(C6)_{49}(C12CE)_4$ and $Au_{220}(C6)_{60}(C12CE)_{15}$, respectively. Likewise, double exchange materials included the following average examples: $Au_{220}(C6)_{35}(MUA)_{35}(C12CE)_5$, $Au_{220}(C6)_{54}(MHOL)_{12}(C12CE)_9$ for the larger core sizes and $Au_{140}(C6)_{45}(MUD)_5(C6CE)_3$, $Au_{140}(C6)_{19}(MUD)_{15}(C12CE)_{19}$ for the smaller core sizes. These compositions are shown to give the reader an idea of the make-up of individual MPCs within the films. It should be noted, however, that core polydispersity will introduce significant variation to the ratios of the ligands [6]. The greater propensity for longer chainlength ligands to exchange with shorter surface ligands was also evident, as seen with MUA versus MHOL in the Au220-MPC examples and C12CE versus C6CE in the Au140-MPC examples given above.

Silanization of glass slides

Piranha cleaned[1] glass slides were immersed in heated mixtures of a specific silane, 2-propanol, and purified water for 45 min. For dithiol-linked and ester-coupled MPC films, the silanes 3-mercaptopropyl trimethoxysilane (3-MPTMS) and hydroxymethyl triethoxysilane (HMTES) were used, respectively. Slides were rinsed with 2-propanol, dried with nitrogen, and cured in a 100 °C oven for at least 1 h.

Dithiol-linked CE-MPC film growth

All MPC films were prepared using ‘‘dip cycle’’ methods (described below) where a single dip cycle consisted of a silanized glass slide being immersed in two solutions, one containing a linking ligand and the other being a CE-MPC solution. Films assembled with dithiol ligands as linking mechanisms were prepared using two dipping solutions: a linker dithiol solution (2.5 mM 1,9-nonanedithiol or 1,6-hexanedithiol in ethanol) and a CE-MPC solution (10 mg CE-MPC in 10 ml of dichloromethane). The CE-MPCs varied by the MPC cluster size and/or CE chain length (n) and were completely soluble in both ethanol and dichloromethane. A dip cycle consisted of immersing the silanized slide in the dithiol solution for up to 15 min followed by a 1 h dip in the CE-MPC solution. After each dip, the slides were rinsed thoroughly with either ethanol or dichloromethane depending on the preceding solvent of the dip, and dried under a stream of nitrogen. UV–VIS spectroscopy (Jasco 550), was performed after every two dip cycles and growth was continued until the film reached a desired thickness based on the absorbance of the film at 350 nm.

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[1] Warning: Use extreme caution when working with Piranha (1:3, H2O2:H2SO4) solution as it reacts violently with all organic materials.

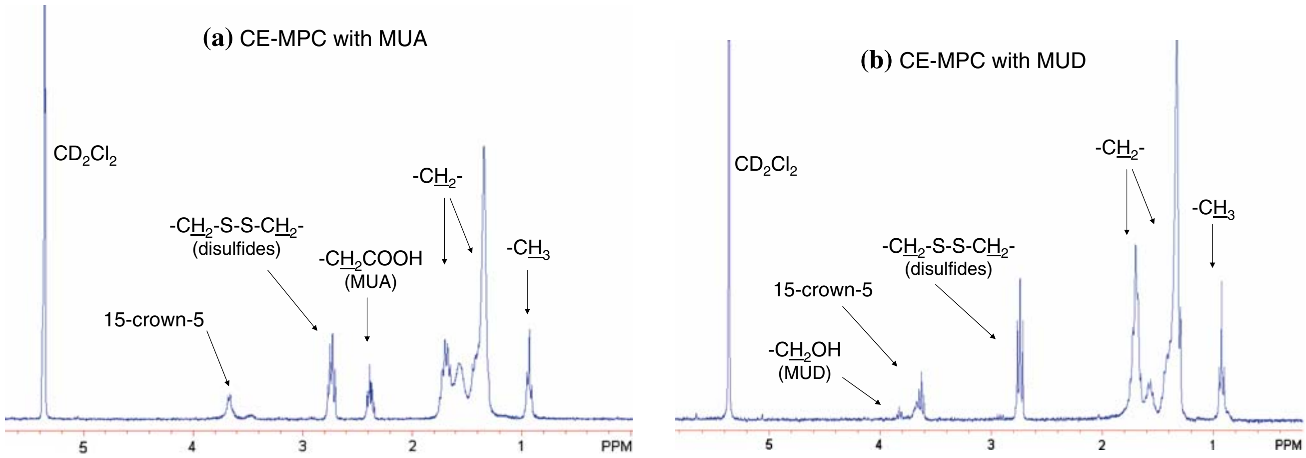

Fig. 1 NMR spectra of MPCs after simultaneous exchange with 15-crown-5-dodecanethiol ligands and (**a**) 11-mercaptoundecanoic acid or (**b**) 11-mercaptoundecanol. NMR spectra are of the disulfides liberated upon oxidative decomposition treatment of the MPCs with iodine [6]

Ester-coupled CE-MPC film growth

Prior to ester-coupled film growth, MPCs were double-modified with CE ligands and either MUA or an alcohol-terminated ligand (e.g., MUD or MHOL). Films assembled with ester-coupled covalent linkages were prepared using two dipping solutions: a MUA-CE-MPC solution and a mercapto-alcohol exchanged CE-MPC solution (10 mg MUD-CE-MPC or MHOL-CE-MPC in 10 ml dichloromethane, respectively). Each solution also contained 3–4 mg 1,3-dicyclohexyl-carbodiimide (DCC) and 2–3 mg 4-(dimethylamino)-pyridine (DMAP) as a coupling reagent and catalyst, respectively [30]. To initiate film formation, a 3-hydroxymethyl triethoxy silane (3-HMTES)-modified glass substrate was immersed in a solution of MUA-CE-MPCs and ester-coupling reagents where carboxylic acid groups on the MPC react with the surface bound hydroxyl groups to form an ester bridge and anchoring a layer of MPCs to the substrate. This process is repeated, alternating between 1 h immersions in MUD-CE-MPCs (10 mg MUA-CE-MPC in 10 ml dichloromethane) and MUA-CE-MPCs (10 mg MUD-CE-MPC in 10 ml dichloromethane) solutions, a dip cycle, to effectively build a covalently networked MPC film (see Scheme 2) [29, 30]. Similar to the dithiol-linked films, the slides were thoroughly rinsed with dichloromethane and dried under a stream of nitrogen before spectroscopic measurements were made to determine growth progress (after every two dip cycles) by monitoring the absorbance at 350 nm. In a previous, detailed report [29], our group has successfully shown that ester-coupling can be used to assemble multi-layer MPC films, including spectroscopic evidence of the interparticle ester bonds when this procedure is used.

Metal ion testing procedure

Both types of films were tested for a spectroscopic response to successively higher potassium ion concentrations ranging from 0.05 to 4.0 mM K^+ in purified water (KNO_3), ethanol (KNO_3), and dichloromethane ($KC_2H_3O_2$). With eventual clinical use in mind for these films, the concentrations of potassium were specifically chosen to be at or below typical physiological levels in blood and urine, approximately 3–5 and 30–90 mM, respectively [15, 16]. A typical metal ion testing procedure involved taking a UV–VIS spectrum of a dry film inside an empty cuvette, a dry baseline signal. The film was then immersed in a pure solvent for several minutes and another spectrum was recorded, a wet baseline signal. Immersion in solvent caused fluctuations in absorbance intensity, partially from slide and cuvette positioning, but never shifted the SPB. The film was then dried in a stream of nitrogen, immediately inserted into a cuvette filled with K^+ solution, and a spectrum recorded. In the event that no change in the SPB was recorded, the film was allowed to soak for 15 min before another measurement was taken to see if the metal response was kinetically challenged on the timescale of the experiment. This wet spectrum was then compared to the wet baseline to look for shifts in the SPB that would be independent of film swelling. During all of the spectroscopic measurements particular attention was paid to the shape and position of the SPB. In all cases, when a shift was observed, it was instantaneous and the first derivative of the spectrum was used to identify the λ_{max} positions.

Results and discussion

It is hypothesized that if CE-MPC films are to be used as metal ion sensors, they would require certain structural features. First and foremost, CE-MPC assembled films require the linking and sensing mechanisms to be completely separate [10]. Second, it is thought that these films must maintain a great deal of flexibility within their networks, both in terms of the ionophores' ability to coordinate metals effectively and the film's ability to swell in the presence of a solvent. These two types of flexibility would impact the core spacing within the film. Lastly, since the film is already in a highly constrained architecture compared to solution MPCs, any response to metal ions in solution would require a film of substantial thickness as a means of achieving effective signal-to-noise levels. All of these properties seem to be dependent upon the mechanism of networking the CE-MPC films.

Two types of film assemblies, dithiol-linked and ester-coupled films (Scheme 2), were investigated for these specific characteristics. The nomenclature for identifying the composition of each film was to list CE-ligand chain-length, followed by the linker employed, and the core size of the MPC. For example, the notation C12-CE, C9-dithiol, Au140-MPC indicates a film of smaller MPCs modified with 12-mercaptododecane-15-crown-5 and linked together with nonanedithiol. Similarly, the notation C12-CE, MUA/MUD, Au140-MPC is a film where MPCs with carboxylic acid groups (MUA) were ester-coupled with nanoparticles having alcohol groups (MUD).

Growth dynamics

Growth dynamics and film structure were examined for CE-MPC films formed using dithiol linkages, specifically hexanedithiol and nonanedithiol bridging ligands. Films with varying parameters (i.e., core size, CE-ligand length, linker molecule, and reaction solvent) were assembled with growth progress monitored spectroscopically, as previously described [10, 25, 26, 29]. Film assembly was conducted in the only two solvents found that completely dissolved the CE-MPCs, ethanol and dichloromethane, in order to avoid precipitation of material onto the substrate. Representative examples of some of these results are shown in Fig. 2. While different growth rates were observed, the most significant result here is that all the dithiol-linked films showed measurable growth regardless of core size, linker length, or CE ligand length. Moreover, these films were grown to thicknesses comparable to other types of assembled MPC systems [10, 25, 26, 29]. The observed growth dynamics of dithiol films allowed for the assembly and eventual metal testing of a wide variety of films. One noteworthy trend was that films grown in dichloromethane (lower two curves) exhibited a substantially lower rate of growth (as seen by the slope of the trend lines) compared to films grown in ethanol (upper three curves). A more direct comparison of this trend is seen in Fig. 2 where films with identical components (C12CE, C9-dithiol, Au220-MPC) but differing only in solvent environment showed extremely different growth rates. This rather drastic difference in film growth for the two solvents is not completely understood but is at least partially due to the superior solubility of the dithiol linker in alcohol [31]. In a somewhat surprising result, we were able to assemble films with both C6- and C9-dithiol linkers, though significant interdigitation of the MPCs is expected in films of this nature rendering the size of the linker compared to the peripheral ligands a less significant factor [25, 26, 29]. Attempts to attain similar growth without exposure to any linker resulted in an insignificant amount of growth.

Figure 3 shows the spectra of films formed from identical CE-MPCs in terms of crown ether ligands and core size, but with different lengths of dithiol linking ligands. As expected, the SPB of the film formed with the shorter linker, hexanedithiol, exhibits a red shift, an indication that the films are slightly more compact or aggregated than the nonanedithiol-linked films [15, 25]. This subtle shift of the SPB in response to only a three methylene unit change in the linker reiterates the sensitivity of this signal to the local environment around the nanoparticle cores. The response of these dithiol films to metal ions is discussed in a later section.

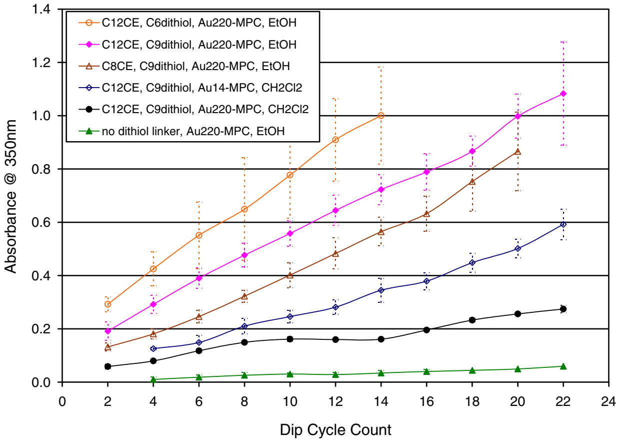

Fig. 2 Representative examples of multi-layer growth of CE-MPC films using dithiol linkages and monitored spectroscopically. Growth trends for films not exposed to solutions of dithiol linker and without CE ligands (▲) is included for comparison. Each point indicates an average response of 4 individual films of that type ($n = 4$) and, in some cases, error bars are smaller than the symbol representing the average

An alternative method of growing thicker CE-MPC films is to assemble multi-layer films via ester-coupling reactions [29]. As discussed in the experimental section, the procedure for growing ester-linked MPC films first requires performing simultaneous, double place-exchange reactions on MPCs to create carboxylic acid functionalized (e.g., MUA-CE-MPCs) and hydroxyl functionalized (e.g., MUD-CE-MPCs) nanoparticles. As these materials are assembled into film geometries, several parameters can be adjusted including the chainlength of the CE ligands, the length of the ester coupling bridge, and the cluster core size. Figure 4 tracks the growth for several representative ester-coupled films grown with MPCs having various characteristics. Again, we show that all the different types of MPCs resulted in film growth except for when coupling reagents were omitted from the procedure (lowest curve). As a general trend, ester-coupled CE-MPC films grow at a lower rate compared to both the dithiol-linked films (Fig. 2) or films grown from similar MPCs lacking CE moieties (top curve) [29]. This observation is understandable considering the ester-coupling linking mechanism is a much more complex interaction compared to the dithiol linkage and that the presence of the CEs most likely complicates the required sterics of the coupling reaction. Additionally, film growth with MPCs featuring MUD, a longer alcohol terminated ligand, seemed more efficient than growth with the shorter MHOL alcoholic ligands. Nevertheless, all ester-coupled CE-MPC films were successfully grown and represent a second category of films with a wide variety of properties that were available for metal testing.

The SPB from UV–VIS spectra of this type of assembled films can be used to ascertain structural information. Prominent, well-defined SPBs, are usually only observed with larger MPCs (e.g., Au220-MPC) or with smaller MPCs that are, by necessity in the film confirmation, forced to be in close proximity [25, 26, 29]. Representative spectra for several ester-coupled films of similar thickness (i.e., absorbance at 350 nm), with and without CE ligands, are shown in Fig. 5. As expected, the intensity and definition of the SPB is dominated by the core size of the nanoparticles, with films composed of Au220-MPCs showing larger and more pronounced SPBs and the Au140-MPC films displaying much more subtle SPBs. It can be speculated that the difference in size of the SPB between the two Au220-MPC films may be a reflection that accommodating the more bulky C12CE ligands may necessitate greater interparticle spacing within the film.

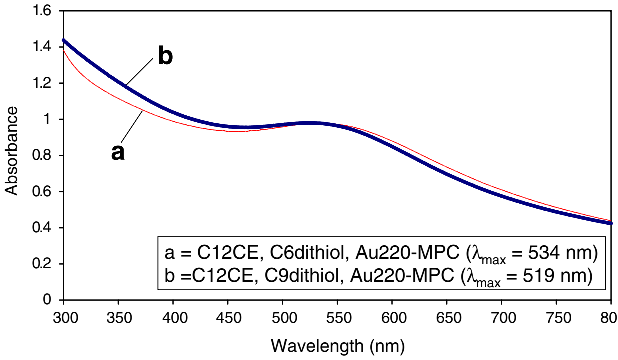

Fig. 3 UV–VIS spectra of dry, dithiol-linked CE-MPC films assembled using (**a**) hexanedithiol (C6-dithiol) and (**b**) nonanedithiol (C9-dithiol) linkers, thinner and thicker traces, respectively

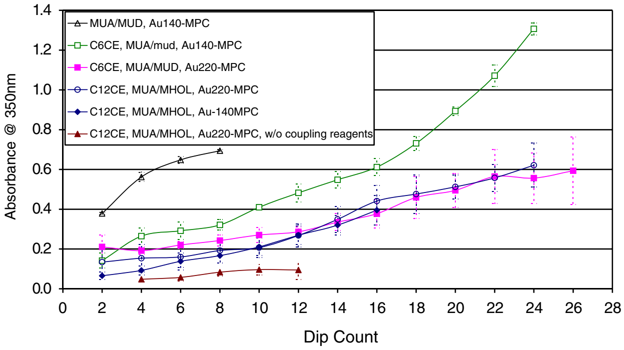

Fig. 4 Representative multi-layer growth of various dry CE-MPC films assembled with ester-coupling reactions. Growth trends for films assembled without coupling reagents (▲) or without CE ligands (△) are included for comparison. Each point indicates an average response of 4 individual films of that type (n = 4) and, in some cases, error bars are smaller than the symbol representing the average

Response to metal ions in solution

A networked film of CE-MPCs should be able to respond to metal ions in the same manner as in solution [15, 16]—a function of core spacing and aggregation. That is, upon exposure to metal ions that can coordinate within the CE moieties in the ''sandwich'' configuration observed by Chen, the spacing between the cores should exhibit a small but measurable change if the film architecture is flexible enough. Two levels of flexibility were hypothesized to be essential for metal detection: (1) flexibility of the film to swell in the presence of a solvent and (2) flexibility of the CE ligands to effectively coordinate the metal ions. MPC films without CE moieties, including those dithiol-linked [23], electrostatically bridged [23, 25, 26, 32], and ester-coupled [29], have already been shown to be flexible enough to swell in the presence of organic solvents and vapors. Thus, it is not unreasonable to assume that films functionalized with CEs can swell and then react to the presence of specific metal ions, with the SPB undergoing a small red or blue shift with decreasing or increasing core spacing [27], respectively. The dielectric effect on the SPB [14, 33] is expected to be minimal since, among other

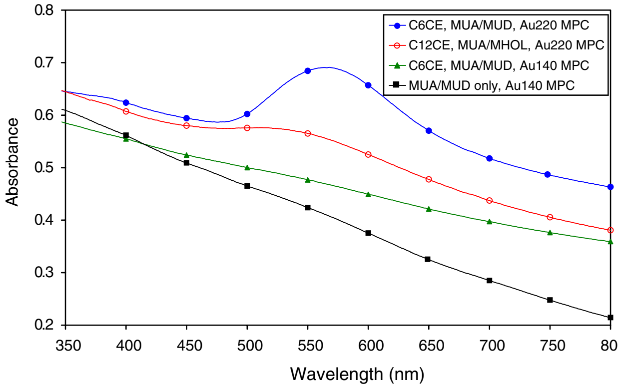

Fig. 5 UV–VIS spectra of ester-coupled films, grown with CE-MPCs of varying properties to similar thicknesses (absorbance at 350 nm) and measured in the dry state. Ester-coupled growth for an MPC film without CE ligands is included for comparison (■)

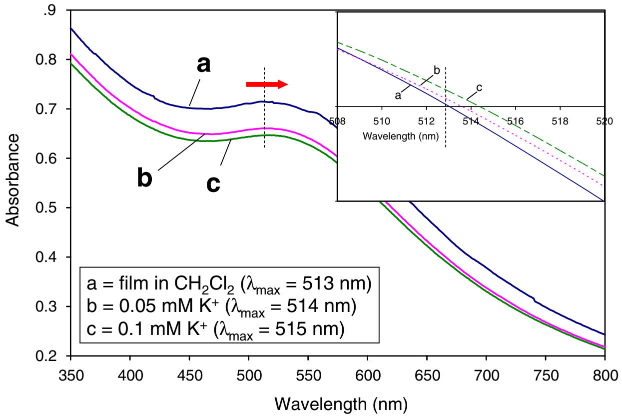

Fig. 6 UV–VIS spectra showing metal response of a C12CE, C6-dithiol, Au220-MPC assembled film in CH$_2$Cl$_2$ with (**a**) 0 mM K$^+$, (**b**) 0.05 mM K$^+$, (**c**) 0.1 mM K$^+$. A very slight red shift is observed in the presence of K$^+$ metal ions. Inset: First derivative plots of the expanded spectra where $\lambda_{max} = x$ intercept. Note: Dotted vertical line indicates the position of λ_{max} of spectrum (**a**)

reasons,[2] the film is already swelled in solvent when metal is introduced and because the change of refractive index at the interface of the MPC and the organic solvent, both non-aqueous, is not substantially abrupt [34, 38].

With a large number of parameters to adjust for each CE film, numerous films were constructed and exposed to concentrations of potassium that were either at or below physiological relevance, with only a few having a measurable and repeatable response to the presence of the metal. None of the films responded to aqueous solutions of potassium, presumably due to the insolubility of the nanoparticles in this medium rendering the film incapable of significant swelling. Only certain films exposed to potassium solutions of ethanol and dichloromethane, solvents known to significantly swell MPC film assemblies, were able to respond to the presence of potassium ions. These reactive films are discussed in more detail below. It should be noted that the films found to be responsive toward potassium ions were also tested in the presence of copper ions, species too small to coordinate with the 15-crown-5 moieties [10]. In all the cases where copper ions were introduced there was no discernable film response recorded, illustrating the selectivity of the films for potassium ions (results not shown) [10, 15, 16].

Considering the aforementioned criteria about flexibility, and the knowledge that most MPC films have a high degree of interdigitated ligands [25], the dithiol films are constrained by their own linking mechanism and are capable of swelling only to the extent of the linking chain. The cores of individual MPCs in hexanedithiol and nonanedithiol films would only be able to separate by a maximum of approximately 6 and 9 methylene units (6.5 and 10.0 Å), respectively. Accordingly, all of the films linked with dithiols showed almost no response when exposed to solutions of potassium ions, indicating perhaps that these films are too rigid for this application. Figure 6 depicts the *most* substantial SPB shift observed from dithiol-linked films, with λ_{max} changing from 513 to 515 upon exposure to K$^+$ as seen in the first derivatives of the spectra (inset). If the films are assumed to instantaneously swell in the presence of solvent as had been previously recorded [25, 26], ''sandwiching'' of K$^+$ by CE groups, a comparatively slower process, should yield a small red shift. The response, however, is minimal and it appears the dithiol films are limited in the first type of flexibility required for metal detection—the ability to swell.

Unlike the dithiol-linked films, ester-coupled films are already known to swell significantly in the presence of solvents [29] and should be flexible in that respect. When certain ester-coupled films were tested for a metal response, however, both a red shift (λ_{max} = 526 → 533 nm), as shown in Fig. 7, and a blue shift (λ_{max} = 594 → 584 nm), as shown in Fig. 8, were observed. The magnitude of both types of shifts were expectedly small but were highly repeatable on multiple samples. Additionally, the nature of the shift, red versus blue, seems to be directly related to the second aspect of required flexibility—that of the CE ligands themselves. The more flexible ligands with longer chainlengths (e.g., C12CE in Fig. 7) have the conformational freedom to coordinate to the metal ions in the sandwich-like configuration reported by Chen. In such cases, the CE–metal ion–

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[2] Several reports [34, 35] indicate that the dielectric effect on the SPB is substantially and specifically dampened with the use of thiol-capped nanoparticles and that a change in interparticle spacing is the most likely sensing event [13, 25, 36, 37]. Based on these reports, the film geometry used in this study is most likely even less sensitive to dielectric effects.

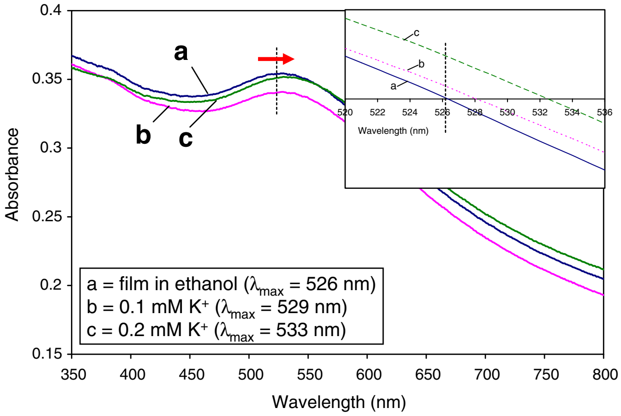

Fig. 7 UV–VIS spectra showing metal response of C12CE, MUA/MHOL, Au220-MPC ester-coupled films in ethanol with (**a**) 0 mM K$^+$, (**b**) 0.1 mM K$^+$, (**c**) 0.2 mM K$^+$. A red shift is observed in the presence of K$^+$ metal ions. A similar shift was observed with C12CE, MUA/MUD, Au220-MPC ester-coupled films (not shown). Inset: First derivative plots of the expanded spectra where $\lambda_{\max} = x$ intercept. Note: Dotted vertical line indicates the position of $\lambda_{\max}$ of spectrum (**a**)

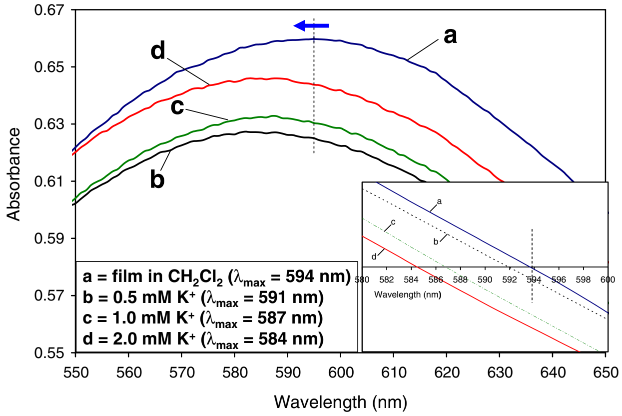

Fig. 8 UV–VIS spectra of SPB region showing metal response of C6CE, MUA/MUD, Au220-MPC ester-coupled films in CH$_2$Cl$_2$ with (**a**) 0 mM K$^+$, (**b**) 0.5 mM K$^+$, (**c**) 1.0 mM K$^+$ and (**d**) 2.0 mM K$^+$. A blue shift is observed in the presence of K$^+$ metal ions. Inset: First derivative plots of the expanded spectra where $\lambda_{\max} = x$ intercept. Note: Dotted vertical line indicates the position of $\lambda_{\max}$ of spectrum (**a**)

CE ''sandwiches'' simply draw the film into a more compact structure (i.e., more aggregated) and the spectroscopy reveals a small red shift. On the other hand, when these films lack this type of flexibility, such as when the CE ligands are very short (C6CE in Fig. 8), a unique and opposite blue shift is observed.[3] It is suggested that this blue shift results from the structural and spatial constriction of this type of system. The only way for the CE-MPCs to coordinate a metal ion without the flexibility of the CE ligands is for the nanoparticles themselves to create more spatial freedom. Sandwiching of the metal ion occurs only after the cores move apart to accommodate the coordination geometry requirements. Thus, a blue shift is believed to be appropriate.

Conclusions

The growth dynamics and metal ion sensitivity of a novel set of ionophoric, assembled MPC films, equipped with separate sensing and linking ligands and featuring either dithiol or ester-coupling linking mechanisms, were explored in this paper. Films of both types of connectivity and a variety of differing core sizes and chainlengths were successfully grown for the first time. Dithiol films were found to be largely unresponsive as metal ion sensing materials, most likely due to a lack of overall film flexibility. A number of ester-coupled films, however, responded to potassium concentrations well below that found in blood and urine [15, 16], suggesting that these films have adequate sensitivity as potential sensing materials. Certain ester-coupled films that were examined exhibited a contraction and subsequent red shift of the SPB in the presence of specific metal ions. These films are believed to swell in the presence of solvent and then aggregate slightly with the formation of CE–metal ion–CE sandwich connections between cores. Films with less flexible sensing moieties, also ester-coupled but with shorter chainlengths on the CE ligand, displayed a blue shift upon exposure to metal ions. This opposite effect is most likely the result of the less flexible film having to accommodate the more rigid steric bulk and restrictive alignment of the sandwich linkage.

As expected for very thin and structurally complex films, the magnitude of the shifts is very small and amplification of the signal by further increasing film flexibility remains a goal of future studies. This work does, however, clearly define the importance of flexibility within these films, both in the linking and sensing mechanisms, if they are to be utilized as metal ion sensors. We continue to explore strategies of increasing film flexibility, including electrostatic and covalent linking mechanisms that allow for greater film movement within even thicker films. The inclusion of several chainlengths of CE ligands onto the MPCs might also increase the ability of the film to coordinate metal ions. One can envision films of this nature with a variety of different-sized CE cavities to detect multiple targeted metal ions. Likewise, research aimed at generating a parallel aqueous system using citrate-stabilized MPCs in networked films is currently underway [39, 40].

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[3] Particular emphasis was placed on analyzing the repeatable spectral shifts in the SPB of the MPC films upon metal exposure. The magnitude of the SPB (Abs. maximum) often fluctuated, as see in Figs. 6–8, with different films and irreproducible positioning of the film in the cuvette.

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