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Self-Defensive Biomaterial Coating Against Bacteria and Yeasts: Polysaccharide Multilayer Film with Embedded Antimicrobial Peptide

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Prevention of pathogen colonization of medical implants is a major medical and financial issue since infection by microorganisms constitutes one of the most serious complications after surgery or critical care. Immobilization of antimicrobial molecules on biomaterials surfaces is an efficient approach to prevent biofilm formation. Herein, the first self-defensive coating against both bacteria and yeasts is reported where the release of the antimicrobial peptide is triggered by enzymatic degradation of the film due to the pathogens themselves. Biocompatible and biodegradable polysaccharide multilayer films based on functionalized hyaluronic acid by cateslytin (CTL), an endogenous host-defensive antimicrobial peptide, and chitosan (HA-CTL-C/CHI) were deposited on a planar surface with the aim of designing both antibacterial and antifungal coating. After 24 h of incubation, HA-CTL-C/CHI films fully inhibit the development of Gram-positive *Staphylococcus aureus* bacteria and *Candida albicans* yeasts, which are common and virulent pathogens agents encountered in care-associated diseases. Hyaluronidase, secreted by the pathogens, leads to the film degradation and the antimicrobial action of the peptide. Furthermore, the limited fibroblasts adhesion, without cytotoxicity, on HA-CTL-C/CHI films highlights a medically relevant application to prevent infections on catheters or tracheal tubes where fibrous tissue encapsulation is undesirable.

1. Introduction

Implantable medical devices are widely used in surgery not only to replace altered or lost tissues but also in critical care for fluid or gas administration using catheters or tracheal tube, respectively. These devices constitute an open gate for pathogens invasion.^[1] Prevention of pathogen colonization of medical implants constitutes a major medical and financial issue since nosocomial infection represents one of the most serious complications after surgery or critical care. Indeed each year in Europe, 5% of patients admitted to hospitals suffer from hospital-acquired infections leading to a mortality of 10%.^[2] *Staphylococcus aureus*, a Gram-positive bacterium, is responsible for hospital-acquired infections especially in immunocompromized patients. It is one of the most virulent bacteria leading to high rates of device-related systemic infections and mortality.^[3] A recent study has genetically characterized the strains of *S. aureus*

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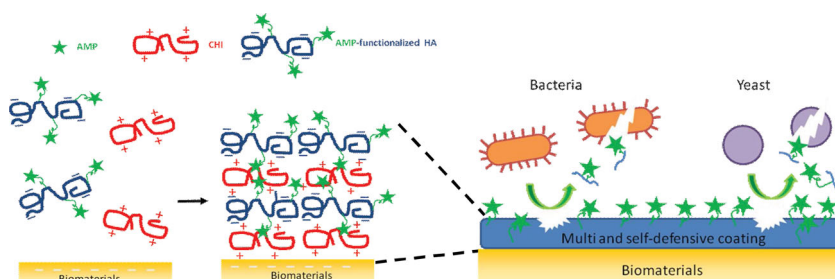
responsible of catheter-related infections and demonstrated that 82% of these strains are methicillin resistant and contain numerous genes involved in biofilm formation and bacterial dispersion.^[4] *Candida albicans*, the most common human yeast pathogen, possesses the ability to form biofilms that are sources of local and systemic infection. Moreover *C. albicans* biofilms allow the formation of *S. aureus* microcolonies on their surface and even enhanced *S. aureus* resistance to antibiotics.^[5] When associated with bacterial infections, fungal proliferation induces an increased frequency or severity of diseases.^[6–8] The recent resistance of *C. albicans* to antifungal therapies^[9–10] and of *S. aureus* to antibiotics points out the need of multifunctional coatings that prevent infections of both yeast and bacteria.

Various approaches based on immobilization or release of bactericidal substances, using self-assembled monolayers or grafting of polymers have been explored and extensively reviewed.^[11,12] Polyelectrolyte multilayer (PEM) films, based on an alternated deposition of polycations and polyanions onto a solid surface, emerged as a simple and efficient approach to functionalize surfaces in a controlled way.^[13,14] The first antibacterial PEM films were designed by insertion of silver nanoparticles.^[15–20] Later on, hydrophobic bactericide using dendritic block copolymer^[21] and liposomes containing silver ion^[22] were inserted in PEM films to obtain efficient bactericidal coatings. Chitosan based PEM films were demonstrated to be antibacterial against *Escherichia coli* and *Enterococcus faecalis*.^[16,23,24] Antibiotics, like gentamicin, have been inserted in hydrolysable^[25] or crosslinked PEM films^[26] to be later released. Despite an improvement of the antibacterial activity of the films, the use of antibiotics or silver particles have serious drawbacks because of their limited efficiency, their toxicity or their role in the emergence of multi-resistant pathogens.^[27,28]

Natural antimicrobial peptides (AMPs), secreted by numerous living organisms against pathogens, gain increased attention due to their broad spectrum of antimicrobial activity and their low cytotoxicity.^[12] They predominantly cause disruption of the membrane integrity of pathogen agents and thus unlikely initiate the development of resistance.^[12] Positively charged AMPs were already used as a part of the PEM architecture to obtain antibacterial effect by contact^[29] or by release.^[26,30] Guyomard et al. succeeded in embedding in PEM films a complex of poor water soluble AMPs and amphiphilic polyelectrolytes. They obtained antibacterial activity against Gram-positive bacteria.^[31] Active PEM films with embedded antifungal peptides were also reported.^[32,33] Yet, it would be of high interest to design coatings bearing both antibacterial and antifungal properties. Up to now, only few systems share both properties. They are mainly based on silver coating^[34] or quaternary ammonium cationic molecules as surfactant,^[35] synthetic polymer,^[36] or silane.^[37]

To our knowledge, no coating based on AMP peptides possessing both properties has been reported so far. To achieve this goal, we used bovine cateslytin (CTL), a Chromogranin A (CGA) derived peptide, an endogenous protein, secreted with its numerous

natural derived peptides by nervous, endocrine and immune cells during infection^[38] acting in the innate immunity system.^[39] CTL, an AMP corresponding to CGA344–358, acts in the micromolar range with a wide spectrum of antimicrobial activities against Gram-positive bacteria, yeasts and filamentous fungi, without cytotoxic effect on mammalian cells.^[40,41] Moreover, it is very stable against bacterial proteases.^[42] We used polysaccharide multilayer films based on CTL-C-functionalized hyaluronic acid as polyanion and chitosan as polycation, (HA-CTL-C/CHI), that were deposited on a planar surface with the aim of designing a self-defensive coating against both bacteria and yeasts (Scheme 1). A cysteine residue (C) was added at the C-terminal end of the CTL sequence to allow its grafting to HA. HA and CHI are biodegradable by enzymatic hydrolysis with hyaluronidase^[43] and chitosanase^[44] respectively. Both polysaccharides are already widely used in biomedical applications due to their interesting intrinsic properties.^[45,46] The ability of *Staphylococcus*,^[47] *Candida* species^[48] and *M. luteus* to degrade HA, by producing hyaluronidase, allows the CTL-C to be released from PEM films only in the presence of the pathogens. Release of antibacterial compounds (AMPs or classical antibiotics) are usually obtained by passive diffusion from the films at physiological pH^[31,32] or by pH-induced degradation of the films.^[25,30] Pavlukhina et al. reported the release of antimicrobial agents using pH variations associated with growth of bacteria as an internal trigger to release.^[26] This coating can thus be named as self-defensive as it is related to a local change of the environment of the coating due to the pathogens themselves. This was the first system developed based on this idea. We developed herein a new self-defensive coating where the release of the antimicrobial peptide is triggered by enzymatic degradation of the film due to the pathogens themselves. Polysaccharides adsorbed mass was determined by Surface Plasmon Resonance (SPR). The buildup and the topography of the films were characterized by Atomic Force Microscopy (AFM). Antibacterial and antifungal activities of HA-CTL-C in solution and HA-CTL-C/CHI films were tested against two strains Gram-positive bacteria, i.e., *S. aureus* and *M. luteus* and one strain of yeast strain *C. albicans*, respectively, by using microdilution assays.^[49] Confocal laser scanning microscopy (CLSM) allowed following the penetration of the fluorescently labeled HA^{FITC}-CTL-C, diluted in solution or embedded in a PEM film, into the cell membrane of *C. albicans*. Finally, the cytotoxicity of HA-CTL-C/CHI films was tested through human gingival fibroblasts (HGFs) viability.



Scheme 1. Schematic representation of CHI/HA multilayers functionalized by an antimicrobial peptide (AMP) and its activity towards bacteria and yeasts based on the degradation of the film.

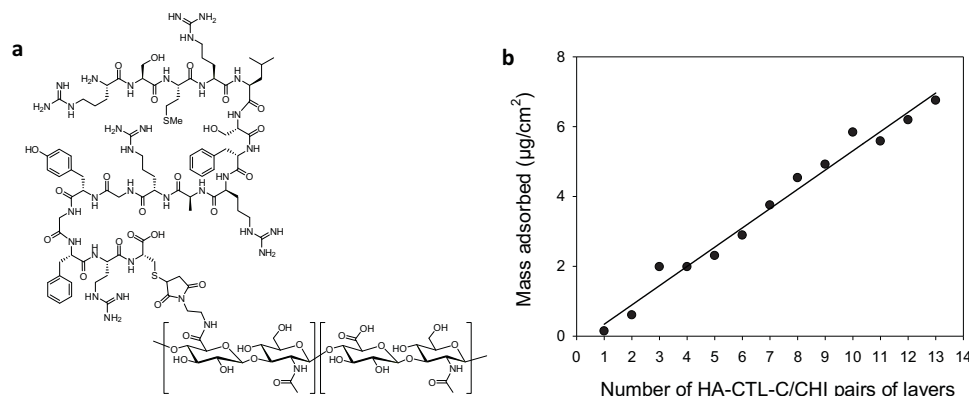


Figure 1. a) Formula of CTL-C functionalized hyaluronic acid, HA-CTL-C, at 5% in grafting ratio. b) Evolution of the mass adsorbed, measured by SPR, (black disks) for the buildup of PEI-(HA-CTL-C/CHI) multilayer film as a function of the number of deposited pairs of layers. The straight line serves to guide the eye.

2. Results and Discussion

2.1. Physical-Chemical Characterization of HA-CTL-C/CHI Films

CTL-C peptide was covalently coupled to HA in two steps using successively the carbodiimide chemistry to graft maleimide functions on HA and the thiol-maleimide coupling reaction to graft CTL-C on the modified HA. Synthetic procedures of CTL-C peptide and its conjugation to HA are described in Supporting Information (SI). After dialysis and freeze-drying, a coupling ratio of 5% was determined by $^1\text{H-NMR}$, corresponding to the grafting of approximately 5 CTL-C peptides for 100 HA dimer units (Figure 1a). The antimicrobial and antifungal activities of CTL and modified CTL were tested in solution against two bacterial strains *M. luteus* and *S. aureus* (ATCC 25923) and a yeast *C. albicans*. Minimal inhibitory concentration (MIC) in peptide of CTL, CTL-C and HA-CTL-C were determined using bacterial and fungal assays described in SI. CTL-C remains antimicrobial at micromolar concentration ($<100\ \mu\text{M}$) and displays an even better activity against *M. luteus* compared to the cysteine free CTL peptide. In comparison with the non-grafted CTL-C peptide, MIC value of HA-CTL-C increases from 35 to $45\ \mu\text{M}$ for *S. aureus* and from 20 to $25\ \mu\text{M}$ for *C. albicans* (Table 1). In the case of *M. luteus*, the MIC of HA-CTL-C ($5\ \mu\text{M}$) is five times higher than that of free CTL-C ($1\ \mu\text{M}$). In spite of this decrease in efficiency, the CTL-C peptide covalently linked to

HA polymer can still be considered as antimicrobial, acting in the micromolar range. The buildup of HA-CTL-C/CHI film was monitored by SPR. A linear increase of the mass adsorbed is observed at each deposited layer of polysaccharide indicating the buildup of the film (Figure 1b). We investigated the topography and the roughness of HA-CTL-C/CHI films at different numbers of deposition steps by means of AFM in dry state (Supporting Information Figure S1). It was difficult to obtain good quality AFM images in the wet state due to the viscoelasticity of the films as we found for HA/CHI films in our previous work.^[50] AFM imaging allows measuring film thickness after scratching. Supporting Information Table S1 summarizes the thicknesses and roughnesses measured by AFM. With 5 bilayers, the surface is already entirely covered with a 5-nm thick film with a roughness of 1.6 nm. As the buildup process goes on, the film thickness increases up to 52 nm at 30 bilayers. The film grows linearly up to 30 bilayers (Supporting Information Figure S2) and the film roughness increases up to 16.5 nm (for 30 pairs of layers).

2.2. Bacterial and Fungal Assays of HA-CTL-C/CHI Films

After characterization of HA-CTL-C/CHI multilayers buildup, the antibacterial and antifungal activities of the functionalized films were evaluated against two strains of bacteria *M. luteus* and *S. aureus* and one of yeast strain *C. albicans*, respectively. The influence of the number of embedded functionalized layers was studied by monitoring pathogen growth for different films with increasing number of HA-CTL-C/CHI bilayers. To this aim, $\text{PEI}-(\text{HA}/\text{CHI})_{15-n}-(\text{HA-CTL-C}/\text{CHI})_n$ films, with $n = 0, 5, 10$ and 15 , and $\text{PEI}-(\text{HA-CTL-C}/\text{CHI})_{30}$ films were built. Pathogens were incubated for 24 h in contact with HA-CTL-C/CHI films at 37°C for bacteria strains and at 30°C for *C. albicans*. For each pathogen, the microbial growth was measured at different times (1, 4, 6, and 24 h) by determination of the optical density at 620 nm (OD_{620}) of the bacterial suspension in contact with the film. The data were normalized to OD_{620} value obtained in similar conditions in the absence of films and are expressed as a percentage of growth (Figure 2a–c). For each tested pathogen,

Table 1. Minimal inhibitory concentration (MIC_{100}) of CTL, CTL-C and HA-CTL-C measured in solution leading to 100% of pathogens inhibition. In the case of HA-CTL-C, the MIC values given correspond to the concentration in CTL-C.

Pathogens	$\text{MIC}_{100}\ [\mu\text{M in peptide}]$		
	CTL	CTL-C	HA-CTL-C
<i>S. aureus</i>	30	35	45
<i>M. luteus</i>	5	1	5
<i>C. albicans</i>	20	20	25

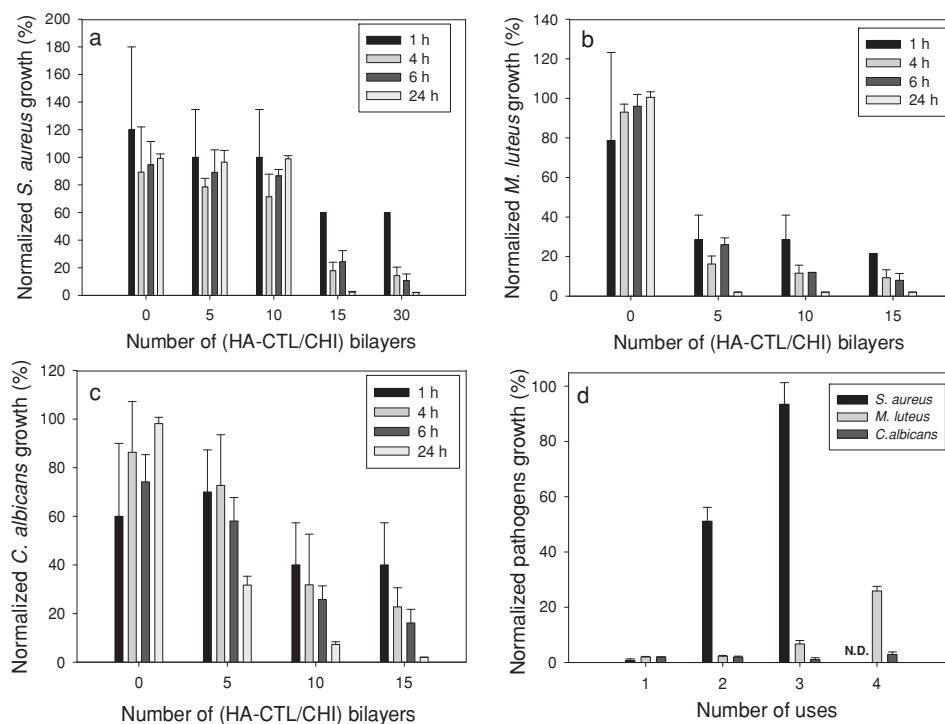


Figure 2. Normalized growth of a) *S. aureus*, b) *M. luteus* and c) *C. albicans* incubated for 1 to 24 h in contact with PEI-(HA/CHI)_{15-n}-(HA-CTL-C/CHI)_n with $n = 0$ to 15 and (HA-CTL-C/CHI)₃₀ multilayer films. d) Normalized growth of *S. aureus* incubated on PEI-(HA-CTL-C/CHI)₃₀ and *M. luteus* and *C. albicans* incubated on PEI-(HA-CTL-C/CHI)₁₅ films, as a function of the number of uses. The film was brought in contact with a fresh pathogen suspension for 24 h. Every 24 h, the supernatant is removed and replaced by a fresh suspension and its OD₆₂₀ is measured. The films were built in 150 mM NaCl at pH 4. The normalization was performed with respect to OD₆₂₀ measured in the absence of film and antibiotics taken as 100% growth and in the presence of antibiotic taken as 0% growth. ND means not determined.

we observed that by increasing the number of HA-CTL-C/CHI bilayers the normalized microbial growth decreases. An important decrease of microbial growth is obtained for at least 5 bilayers for *M. luteus* and *C. albicans* and 15 bilayers for *S. aureus*. After 6 h of incubation, at least 70% of inhibition is obtained with 15 bilayers for all tested pathogens. After 24 h of incubation, the growth of *M. luteus*, *C. albicans* and *S. aureus* are fully inhibited with 5, 15 and 30 HA-CTL-C/CHI bilayers, respectively. These results are in agreement with the MIC values of HA-CTL-C in solution (Table 1) that follow the same trend towards the different pathogens. In order to check if the films can be reused several times as antimicrobial coatings, the growth of the three pathogens was monitored when incubated for 24 h in contact with reused PEI-(HA-CTL-C/CHI)₁₅ films for *M. luteus* and *C. albicans* and PEI-(HA-CTL-C/CHI)₃₀ film for *S. aureus*. To this aim, a fresh pathogen suspension was brought in contact with the functionalized film. After an incubation of 24 h, the supernatant was withdrawn and replaced by a fresh pathogen suspension. After each withdrawal, the OD₆₂₀ of the supernatant was measured to determine pathogen growth after 24 h of incubation. When *M. luteus* and *C. albicans* suspensions in contact with (HA-CTL-C/CHI)₁₅ film are renewed every 24 h, a complete inhibition was observed at least for two and three cycles of use respectively. A significant decrease in efficiency of (HA-CTL-C/CHI)₁₅ film is detectable after the following renewal of pathogens suspension (Figure 2d). *S. aureus* growth is only

inhibited by 40% for the second use of the (HA-CTL-C/CHI)₃₀ film and becomes fully inefficient in the third cycle. In parallel, the supernatants withdrawn were incubated with fresh pathogen suspensions for 24 h and the OD₆₂₀ was also measured (Supporting Information Figure S3). No inhibition of growth was observed showing that there is no or a weak amount (quite less than the MIC) of CTL-C released in solution.

2.3. Mechanism of Pathogen Growth Inhibition of HA-CTL-C/CHI

To clarify the mechanism of HA-CTL-C inhibition, we synthesized fluorescently labeled HA^{FITC}-CTL-C and HA^{FITC} to analyze the films after contact with the pathogens. *S. aureus* and *C. albicans* are known to secrete hyaluronidase, a class of enzymes able to hydrolyze HA.^[47,48] The cutting of one constitutive partner of the film should lead to its degradation as it was observed by Etienne et al.^[51] We were then interested in imaging PEI-(HA^{FITC}/CHI)₁₅ films, by CLSM, before and after 24 h of contact with the pathogens. The three pathogens induce the degradation of HA/CHI films with, however, some differences in the resulting film morphologies (Figure 3). After 24 h of incubation with *S. aureus*, HA^{FITC}/CHI films were almost totally degraded (Figure 3a). The film appears inhomogeneous with fluorescent dots after incubation with *M. luteus* (Figure 3b). *C. albicans* induces the formation of honeycombs in the film

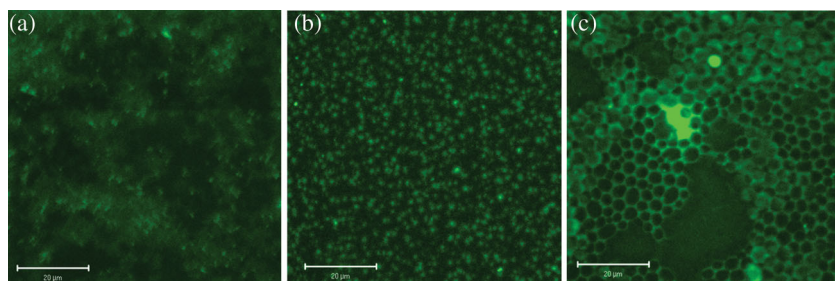


Figure 3. CLSM images of PEI-(HA^{FITC}/CHI)₁₅ after 24 h of incubation with a) *S. aureus*, b) *M. luteus* and c) *C. albicans*. All the films underwent a PFA treatment. The scale bars represent 20 μm.

due to the degradation of HA (Figure 3c). Degradation of HA should release CTL-C in the supernatant and promote the contact between CTL-C peptides and the pathogens. To check this hypothesis, we built hyaluronidase resistant films functionalized by CTL-C. CTL-C grafted on poly(allylamine hydrochloride) was thus synthesized and used to build poly(acrylic acid)/CTL-C functionalized poly(allylamine hydrochloride) (PAA/PAH-CTL-C) film. After 24 h of incubation, (PAA/PAH-CTL-C)₁₅

films show no inhibition against *C. albicans* (data not shown). This emphasizes the fact that the antimicrobial activity of the HA-CTL-C/CHI film is due to its degradation by the pathogens. This property renders the film specifically active in the presence of hyaluronidase secreted by the pathogens. Pathogens thus initiate their own death when brought in contact with the HA-CTL-C/CHI film. Even though the film is degraded with time in the presence of pathogens, it can be reused at least two and three times without losing its activity against *M. luteus* and *C. albicans*.

Using fluorescently labeled CTL-C, a previous study showed that the peptides penetrate into cell membranes and accumulate inside yeasts.^[40,41] The interactions of HA^{FITC}-CTL-C and HA^{FITC} with *C. albicans* was thus studied when solubilized in solution or embedded in multilayer films. After 45 min of incubation at 30 °C with HA^{FITC} or HA^{FITC}-CTL-C in solution, *C. albicans* were observed by CLSM. The fluorescent HA^{FITC}-CTL-C was detectable in cytoplasm without inducing cell lysis (Figure 4a). On the contrary, HA^{FITC} is clearly

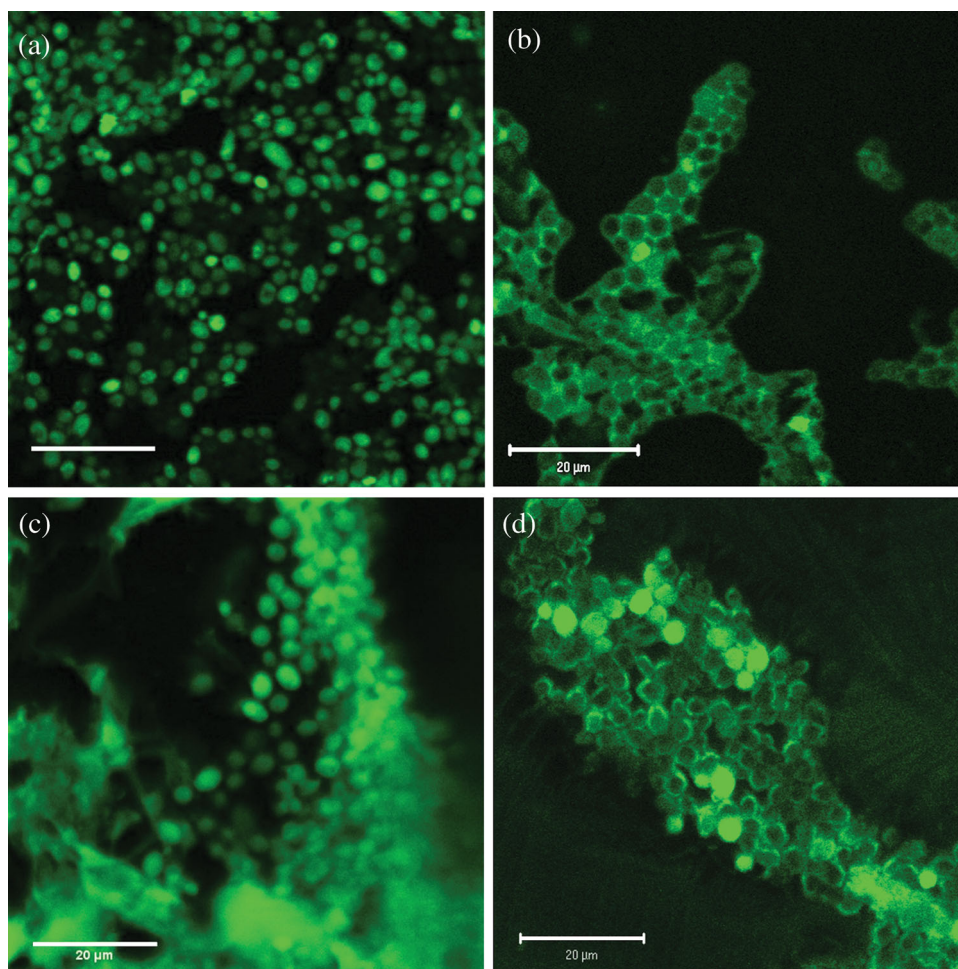


Figure 4. CLSM images of *C. albicans*, after 45 min of incubation a) in the presence of HA^{FITC}-CTL-C in solution (50 μM in peptide), b) in the presence of HA^{FITC} in solution, c) in contact with PEI-(HA^{FITC}-CTL-C/CHI)₁₅, and d) in contact with PEI-(HA^{FITC}/CHI)₁₅ multilayer films. The scale bars represent 20 μm

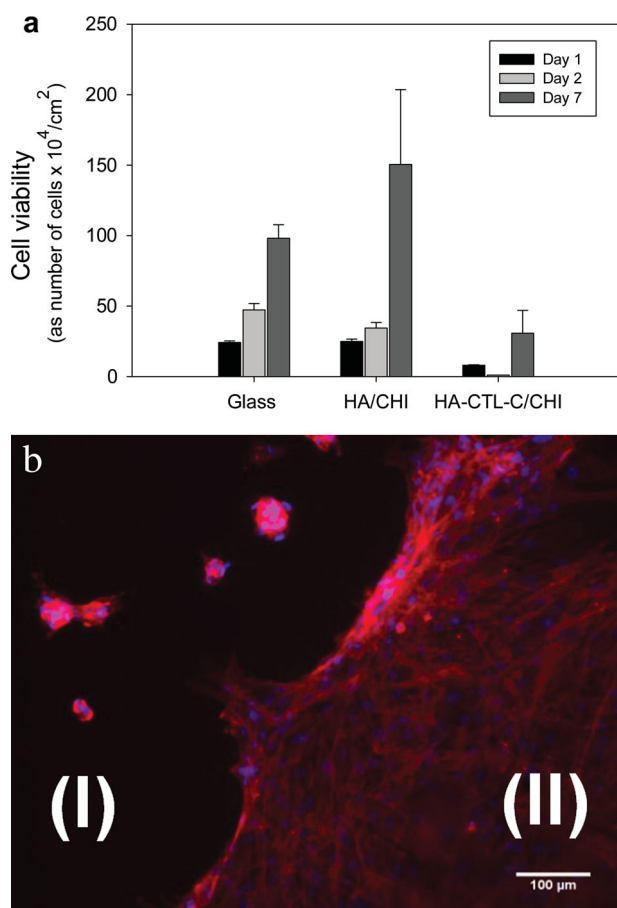


Figure 5. a) Viability of HGFs, evaluated by metabolic activity of cells, cultured on PEI-(HA/CHI)₁₅, named HA/CHI and PEI-(HA-CTL-C/CHI)₁₅, named HA-CTL-C/CHI, films built on glass substrates. Cell viability was determined by Alamar Blue assays after 1, 2, and 7 days of culture. The values represent the mean and the standard deviation of three films. b) Cytoskeleton visualization by actin filament immunofluorescent staining with phalloidin (red labeling) and DAPI nuclei counterstaining (blue labeling) of HGFs after 24 h of culture on half coated glass substrate by PEI-(HA-CTL-C/CHI)₁₅: the areas represent (I) the HA-CTL-C/CHI film and (II) the bare glass substrate.

observed all around the yeast cells, stacking probably on the membranes and leading to a honeycomb structure (Figure 4b). This suggests that CTL-C can cross the cell membrane, even when it is coupled to HA, leading to an accumulation of HA inside the cytoplasm. To image them by CLSM, the films were treated by paraformaldehyde (PFA) to fix the pathogen in contact. This treatment was first applied on the films to evaluate its effect. PFA treatment induces no change in the case of HA^{FITC}/CHI films in contrary to HA^{FITC}-CTL-C/CHI films (Supporting Information Figure S4) where heterogeneities appear. *C. albicans* were incubated for 45 min at 30 °C in contact with PEI-(HA^{FITC}-CTL-C/CHI)₁₅ film and then observed by CLSM. Among the heterogeneities due to PFA treatment, a strong green fluorescence is observed mainly inside the yeast (Figure 4c). In the case of HA^{FITC}/CHI films, a little fluorescence is localized inside the yeasts and only few of them are strongly fluo-

rescent (Figure 4d). In spite of its insertion into the PEM films, CTL-C allows the penetration of HA^{FITC}-CTL-C inside the yeasts explaining the activity of the films.

2.4. Biocompatibility Tests of HA-CTL-C/CHI Films

Finally, it is important to ensure that the film is not cytotoxic to healthy wound healing cells. Fibroblasts are one of the first anchorage-dependent cells to come at an implant surface during the wound healing process. The viability of HGFs cultivated on PEI-(HA-CTL-C/CHI)₁₅ films, compared to PEI-(HA/CHI)₁₅ films and glass substrate, has been evaluated through their mitochondrial activity, monitored by Alamar blue assays. Already after one day, the metabolic cell activity measured on HA-CTL-C/CHI films is lower compared to HA/CHI films and non-coated glass substrate (Figure 5a). The good biocompatibility of HA/CHI films towards HGFs, mediated via CD44 receptor, was already reported in our previous work.^[50] After 7 days of culture, the number of viable HGFs on HA-CTL-C/CHI films represents 25% of viable HGFs on HA/CHI films. The functionalization of HA by CTL-C peptide induces a lower adhesion of HGFs which seems to slow down the proliferation of cells. Knowing that HA-CTL-C in solution at 100 μ M did not show any cytotoxicity (data not shown), such behavior would suggest that the multilayers are not cytotoxic. To discriminate between cytotoxic or low initial adhesion properties of HA-CTL-C/CHI, we performed two experiments. First after 24 h of contact, suspended cells harvested from HA-CTL-C/CHI film supernatant were passed to fresh culture plates. After 24 h of culture, many cells readily attached and spread as fresh cells. Second, we analyzed the biocompatibility of films by a complementary assay based on cell spreading via cytoskeleton arrangement when the cells are seeded on a glass substrate half coated by (HA-CTL-C/CHI)₁₅. After 24 h, HGFs adhere on the glass substrate (Figure 5b, zone II), but to a lesser degree on (HA-CTL-C/CHI)₁₅ film (Figure 5b, zone I). After 24 h of culture, a confluent layer with a typical fibroblastic cell shape and with polymerized F-actin fibers is observed on the glass substrate (Supporting Information Figure S5a). On the HA-CTL-C/CHI film, cells appear less elongated and have a peripheral actin distribution (Supporting Information Figure S5b). This indicates that (HA-CTL-C/CHI)₁₅ films are not cytotoxic but seem rather anti-adherent towards HGFs. It is known that persistent excessive functions of fibroblasts have been linked to detrimental fibrous tissue formation which may cause implant failure. The present results of decreased fibroblast adhesion on functionalized substrate with HA-CTL-C/CHI films shows promise for implant applications.

3. Conclusions

In conclusion, we designed a new surface coating based on polysaccharide multilayer films containing a functionalized HA with 5% of CTL-C, a peptide possessing both antibacterial and antifungal properties. Antimicrobial properties of CTL-C were preserved when grafted on HA either in solution or when embedded into PEM films. After 24 h of incubation,

HA-CTL-C/CHI films fully inhibit the development of *S. aureus* and *C. albicans*, which are common and virulent pathogens agents encountered in care-associated diseases. The presence of CTL-C peptides on HA allows the penetration of the modified polysaccharide inside *C. albicans* after 45 min of contact. The secretion of hyaluronidase by all tested pathogens seems to be responsible for HA-CTL-C release from the film and for its activity. The film can keep its activity during 3 cycles of use against fresh incubated *C. albicans* suspension. Furthermore, the limited fibroblasts adhesion, without cytotoxicity, on HA-CTL-C/CHI films highlights a medically relevant application to prevent infections on catheters or tracheal tubes where fibrous tissue encapsulation is undesirable.

4. Experimental Section

Polysaccharide Solutions: Chitosan (CHI, PROTASAN Ultrapure Chitosan CL213, 260 000 g/mol, DA 83%) was purchased by Novamatrix (Sandvika, Norway). Dried Sodium Hyaluronate (HA, 420 000 g/mol) was purchased by Lifecore (Chaska, USA). Poly(ethylene imine) (PEI, 60 000 g/mol, 50% in water), sodium chloride, sodium dodecyl sulfate (SDS), HCl and NaOH were purchased by Sigma-Aldrich (Quentin-Fallavier, France). All products were used without further purification. 150 mM NaCl solution was prepared with Ultrapure Milli-Q water having a resistivity of 18.2 MΩ cm. CHI and HA solutions were prepared at 0.3 mg/mL in 150 mM NaCl adjusted at pH 4 with NaOH or HCl solutions. HA-CTL-C and HA^{FITC}-CTL-C solutions were prepared at 0.2 mg/mL and 0.1 mg/mL, respectively. PEI solution was prepared at 0.5 mg/mL in 150 mM NaCl solution adjusted at pH 7.5 with NaOH or HCl solutions.

Film Buildup: Before PEM buildup, glass coverslips (Ø = 14 mm; VWR, Strasbourg, France) were cleaned in a SDS solution at 0.01 M, ultrasonicated for 5 min and then submitted to a hot 0.1 M HCl solution for 10 min and finally rinsed with ultrapure Milli-Q water. The precursor PEI layer and CHI/HA films were deposited using an automated spraying device described in a previous work.^[50] CHI/HA-CTL-C and CHI/HA^{FITC}-CTL-C films have been prepared in 24-well plates on PEI precoated glass substrates. 300 µL of the polycation solution were deposited for 5 min on glass coverslips followed by a rinsing step (500 µL) with ultrapure Milli-Q water. Then, 300 µL of polyanion solution were deposited for 5 min followed by a rinsing step (500 µL) with ultrapure Milli-Q water. To test the antimicrobial activity of PEM films versus the number of HA-CTL-C layers, PEI-[HA/CHI]_{15-n}-[HA-CTL-C/CHI]_n with *n* equal to 0, 5, 10, and 15 and PEI-[HA-CTL-C/CHI]₃₀ films were built.

Surface Plasmon Resonance: Surface plasmon resonance (SPR)^[52,53] as some other detection techniques (optical waveguide lightmode spectroscopy, quartz crystal microbalance), provides a label-free, in situ method to monitor the buildup of e.g., a polymer film on a solid surface. When a beam of light passes from a material of refractive index, *n*₁, into a material with a lower refractive index, *n*₂, some light is reflected from the interface. When the angle of incidence of the light, *θ*, on the interface is greater than *θ*_{TIR} = arcsin(*n*₂/*n*₁), the light is completely reflected (total internal reflection). In the case of the SPR instrument used here (SPR Navi 200, Bionavis, Finland), the most refractive medium is a BK7-glass prism. Because the bottom surface of the prism is coated with a thin film of a noble metal (gold), this reflection is not total; some of the light is 'lost' into the metallic film. There then exists a second angle, *θ*_{SPR} > *θ*_{TIR}, at which the intensity of the reflected light goes through a minimum. In addition, an evanescent electrical field travels for a short distance into the medium (e.g., film) from the metallic film. The probing distance reaches generally a few hundreds of nm depending on the refractive index of the probed medium and *θ*_{SPR} is sensitive to the optical characteristics of the deposited film. The reflection curves, i.e., the variation of the intensity of the reflected light with *θ*, corresponding to the successive polymer deposition steps have been analyzed with a

home-made software based on Maxwell's equations. The parameters involved are the refractive indices of the prism, the chromium and gold layers, the polymer film (*n*_{film}) and the buffer solution (*n*_{sol}), as well as the thickness of the chromium and gold layers and of the film (*d*_{film}). From *n*_{film}, *n*_{sol} and *d*_{film}, we derive the mass of film per unit area:

$$m = \frac{(n_{\text{film}} - n_{\text{sol}}) d_{\text{film}}}{dn/dc} \quad (1)$$

where *dn/dc* is the change in refractive index with concentration and is equal to 0.197 cm³/g for polyelectrolytes.^[54] The SPR experiment was performed under a continuous flow rate of 100 µL/min of 150 mM NaCl solution adjusted at pH 4. The time of deposition and of rinsing of polyelectrolytes was fixed at 5 min.

Atomic Force Microscopy (AFM): Atomic force microscopy (AFM) images were obtained in contact mode in dry state with the Nanoscope IV from Veeco (Santa Barbara, CA). The images were carried out with silicon nitride cantilevers, spring constant 0.03 N/m (model MSCATUHW, Veeco, CA). Several scans were performed over a given surface area. These scans had to give reproducible images to ascertain that there is no sample damage induced by the tip. Deflection and height mode images are scanned simultaneously at a fixed scan rate (2 Hz) with a resolution of 512 × 512 pixels. Data evaluation was performed with the NanoScope software version 5.31r1 (Digital Instruments, Veeco). The buildup of the film was made on glass substrate and the film thickness was measured by using the "scratch" method. Profilometric section analyses of a scratched film allowed us to determine precisely the quality of the film and its thickness over the scanned area. The scratches were achieved with a plastic cone tip and were always imaged perpendicular to the fast scan axis. The profiles correspond to a cross section along this axis. The mean thickness of the scratched film was determined by measuring the thickness at least on three areas.

Confocal Laser Scanning Microscopy (CLSM): Confocal laser scanning microscopy (CLSM) observations were carried out with a Zeiss LSM-510 microscope using a 40×/1.31 oil immersion objective and a 0.43 µm z-section interval. FITC fluorescence was detected upon excitation at 488 nm, through a cut-off dichroic mirror and an emission bandpass filter of 505–530 nm (green).

Bacterial and Fungal Growth: To determine the antibacterial activity, microdilution assay was used on two bacterial strains *M. luteus* (A270) and *S. aureus* (ATCC25923). The antifungal activity was tested against one yeast strain *C. albicans*. Bacteria were precultured aerobically in Mueller-Hinton (MH) broth (Merck, Darmstadt, Germany) with agitation at 37 °C for 18 h. *C. albicans* preculture was carried out on a Sabouraud broth (SB) medium (BioMérieux S.A., Marcy l'Etoile, France) with agitation at 30 °C for 24 h. The antimicrobial activity was tested using a mid-logarithmic-phase culture of bacteria or yeast with an initial optical density at 620 nm (OD₆₂₀) of 0.001. For the tests performed in solution, aqueous solutions of CTL, CTL-C and HA-CTL-C were prepared in bacterial or yeast medium. Aliquots of CTL-C or HA-CTL-C (10 µL) were incubated in 96-well microplates (Falcon, Becton Dickinson, USA) with 90 µL of bacteria or yeast at final concentrations of 100 µM to 2 µM of peptide. After 24 h of incubation at 37 °C under gentle stirring, the OD₆₂₀ of the 96-well plate was measured by a microplate reader.^[55–56] MIC₁₀₀, the minimal inhibitory concentration, is the lowest concentration that is able to completely inhibit the growth of bacterial or fungi after 24 h of contact. To test the antibacterial and antifungal properties of the multilayer films, PEI-(HA/CHI)_{15-n}-(HA-CTL-C/CHI)_n with *n* = 0, 5, 10 and 15 and PEI-(HA-CTL-C/CHI)₃₀ films were prepared. 400 µL of a mid-logarithmic-phase culture of bacteria or yeast with OD₆₂₀ of 0.001 were placed in 24-well plate containing multilayer films. For each tested film, 100 µL of the supernatant was taken to measure its OD₆₂₀ by a microplate reader. The withdrawn volume was compensated with the appropriated fresh bacteria or yeast solution of the same measured OD₆₂₀. Intermittent controls were performed by inoculating the culture medium on MH (resp. SB) agar plates by spreading method and counting colonies for verification at different steps. Several controls were used: a fresh medium without inoculation of pathogens was used

to ensure sterility, a mixture of Tetracycline (10 µg/mL) and Cefotaxime (0.1 µg/mL) was used as positive control (90 µL of culture and 10 µL of antibiotics) and a fresh inoculated culture medium without any addition was taken as negative control. For the bacterial and yeast quantification, a conversion factor was devised to convert OD into bacterial and yeast counting, respectively. Briefly, OD of fresh bacteria (respectively yeast) culture was measured at 620 nm and was plated to MH (respectively SB) agar for 24 h at 37 °C (respectively 30 °C). Colony count was performed and plotted versus the OD₆₂₀ and the slope of the linear curve was taken as conversion factor. Pathogen quantification (colony forming unit (CFU) per mL) was performed at time zero and then at each hour for 6 h and then finally at 24 h. For quantification, conversion factors were determined for each strain used separately.^[57] Each assay was performed in triplicate and the experiments were repeated at least three times. The normalized growth of pathogens (%) was estimated by comparing the OD₆₂₀ values in the presence of multilayer films and the positive and the negative controls. The OD₆₂₀ value of control cultures growing in the absence of films and antibiotics was taken as 100% growth (negative control) and the OD₆₂₀ value of cultures growing in the presence of antibiotics (Tetracycline and Cefotaxime) was taken as 0% growth (positive control). The following equation definition was used:

Normalized pathogen growth (%)

$$= \frac{(OD_{620, sample} - OD_{620, positive control})}{(OD_{620, negative control} - OD_{620, positive control})} \times 100$$

To follow the interaction of fluorescently labeled HA^{FITC}-CTL-C in solution and HA^{FITC}-CTL-C/CHI films with *C. albicans*, CLSM was used based on a protocol previously described with few modifications.^[58] Briefly, for experiments done with HA^{FITC}-CTL-C in solution, poly-L-Lysine coated microscopic slides were covered with fresh medium containing *C. albicans* (OD₆₂₀ = 0.001) in SB culture medium and incubated for 24 h at 30 °C without agitation. The medium was then removed and replaced by 50 µM (in peptide) of HA^{FITC}-CTL-C. After an incubation period of 45 min, the slides were washed with fresh culture medium and subsequently treated for 30 min with 4% paraformaldehyde in phosphate buffer saline (PBS) at pH 7.3. After several rinsing steps with PBS, slides were covered with Moviol 4-88 (Aldrich, Steinheim, Germany). For experiments performed with HA^{FITC}-CTL-C/CHI, fresh *C. albicans* medium, previously incubated at OD₆₂₀ = 0.001 in SB culture medium for 24 h at 30 °C without agitation, was put in contact with PEI-(HA^{FITC}-CTL-C/CHI)₁₅ films for 45 min at 30 °C without agitation. HA^{FITC} in solution and HA^{FITC}/CHI films were used as control. *C. albicans* were subjected to optical serial sectioning (0.2–0.3 µm) to produce images in the x–y plane. Each optical section was scanned several times to obtain an average image. Images were recorded digitally in a 768 × 576 pixel format.

Human Gingival Fibroblasts Viability Assays: The biocompatibility of films was tested using human gingival fibroblasts (HGFs). HGFs were extracted from human gingival connective tissue of healthy individuals according to a protocol approved by the ethics committee for patient protection of CPP Strasbourg Hospitals. Cells were grown in DMEM containing 1 g/L of glucose and supplemented with 10% fetal bovine serum and 100 IU/mL penicillin-streptomycin (all from Gibco). Cells were cultured at 37 °C in 5% CO₂ in 75 cm² flasks. HGFs were used between the 6th and the 9th passage. Before cell seeding, glass coverslips (Ø = 14 mm) coated with different architectures were irradiated by UV for 15 min. Then HGFs were seeded at 3 × 10⁴ cells per cm² and cultivated at 37 °C under a 5% CO₂ humidified atmosphere for different culture times (Day 1, Day 2 and Day 7). Cell viability was assessed by Alamar Blue assay (Biosource International). This assay is based on the reduction of the blue, non-fluorescent resazurin dye to the pink and fluorescent resorufin dye by living cells.^[59] The overall conversion rate is proportional to the metabolic activity of living cells.^[60] Viability was assessed for different times 1, 2, and 7 days. After rinsing with PBS, cells were incubated with 10% reagent in complete medium for 2 h. After incubation optical density (OD) at 570 nm and 630 nm were determined with a microplate reader. The percentage of reduction

of Alamar Blue was calculated according to the procedure provided by the manufacturer. The experiments were performed in triplicate. Actin filament staining with tetramethylrhodamine B isothiocyanate coupled phalloidin (Sigma-Aldrich) and DAPI (Invitrogen) nuclei counterstaining were performed as follows: cells were fixed with 3.7% paraformaldehyde for 10 min at 4 °C, permeabilized in 0.25% Triton X-100 in PBS for 10 min, and blocked in 1% BSA-PBS for 30 min. Thereafter, cells were incubated for 30 min at room temperature with 5 × 10^{−5} mg/mL phalloidin followed by nuclear counterstaining with DAPI (50 ng/mL) incubated for 2 min at room temperature. Washed slides were mounted on blades with DAKO fluorescent mounting medium and fluorescence distribution was examined by means of an inverse fluorescence microscope (Axiovert, Zeiss).

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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