Durable and Regenerable Antimicrobial Textiles: Synthesis and Applications of 3-Methylol-2,2,5,5-tetramethyl-imidazolidin-4-one (MTMIO)

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Abstract: A new precursor of halamine compounds, 3-methylol-2,2,5,5-tetramethylimidazolidin-4-one (MTMIO), was synthesized by methylolation of 2,2,5,5-tetramethylimidazolidin-4-one (TMIO) and characterized by ^{1}H-NMR and FTIR. By chemically reacting MTMIO with cellulose, TMIO rings were successfully grafted onto cellulose-containing fabrics. After a subsequent chlorination, the treated fabrics were converted to halamine structures, which then demonstrated effective antibacterial efficacy. As expected, the halamine structure generated from TMIO is much more stable, and therefore, the biocidal functions of the finished materials are more durable. The results indicated that this halamine structure could survive repeated home laundering and would require less frequent chlorine recharging to maintain the biocidal properties. © 2003 Wiley Periodicals, Inc. J Appl Polym Sci 89: 2418–2425, 2003

Key words: functionalization of polymers; halogenation; modification

INTRODUCTION

Clothing and textile materials are good media for growth of bacteria according to recent reports showing that microorganisms could survive on fabric materials for more than 90 days in a hospital environment.[1–2] Such a high survival rate of pathogens on medical use textiles may contribute to transmissions of diseases in hospitals. As a means to reduce bacterial population in healthcare settings and possibly to cut pathogenic infections caused by the textile materials, utilization of antimicrobial textiles in healthcare facilities is considered to be a potential solution. In recent years, the development of antimicrobial textile materials has attracted significant attention from researchers.[3–6] For example, durable and regenerable antimicrobial fabrics were developed by chemically incorporating hydantoin rings to cotton-containing fabrics with dimethylol-5,5-dimethylhydantoin (DMDMH) and monomethylol-5,5-dimethylhydantoin (MDMH), followed by a chlorine bleaching.[7–9] Hydantoin rings bring in amide and dominantly imide halamine structures, which are quite labile to lose active chlorine, and therefore, fabrics treated with DMDMH need frequent chlorine recharging after washing or after certain time of storage.[10] Although the requirement of frequent bleaching perfectly fits into the standard practice of commercial laundry of textiles used in hospitals and hotels, it still posts inconvenience to other users, particularly to apparel customers. Obviously, a new biocidal halamine structure possessing high stability should be investigated.

The stability of halamines is determined by their structures, which generally include imide, amide, and amine halamine bonds.[10–12] The dissociation of chlorine from halamine structures in aqueous solutions follows such an order, that is, imide halamine > amide halamine > amine halamine (Table I). The imide halamine is the least stable structure that can quickly lose active chlorine and return to the precursor. Thus, more imide bonds will result in relatively less durable antimicrobial properties on the materials, which is the reason that DMDMH-treated fabrics have relatively low durability, particularly in washing. One potential solution is to incorporate amine structures to the fabrics because amine halamine is the most stable bond among these halamines. Researchers have found that 1-chloro-2,2,5,5-tetramethylimidazolidin-4-one is the most stable halamine among all of developed halamines in aqueous systems.[12,17] Based on the results, 2,2,5,5-tetramethylimidazolidin-4-one (TMIO)

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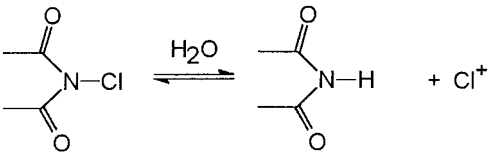
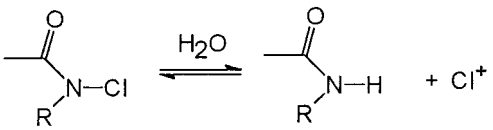
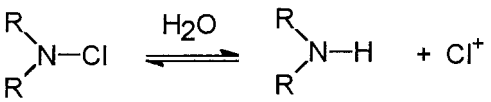
TABLE I
Dissociation Constants of Halamine Compounds

Dissociation reaction	Dissociation constant and example	Reference
Imide structure	1.6×10^{-2}-8.5×10^{-4} Trichlorocyanuric acid	Ref.[13]
	2.54×10^{-4} 1,3-Dichloro-5,5-dimethylhydantoin	Ref.[14]
Amide structure	2.6×10^{-8} 1,3-Dichloro-2,2,5,5-tetramethyl-4-imidozalidinone	Ref.[11]
	2.3×10^{-9} 3-Chloro-4,4-dimethyl-2-oxazolidinone	Ref.[15]
Amine structure	$<10^{-12}$	Ref.[16]
		

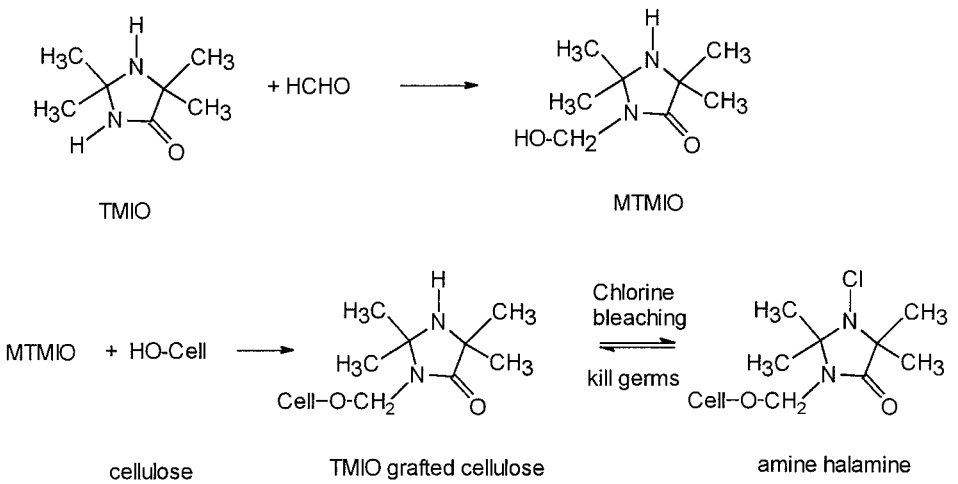
was selected to be grafted onto cellulose in order to bring in the amine halamine structure. To make TMIO reactive with cellulose, a novel compound, 3-methylol-2,2,5,5-tetramethylimidazolidin-4-one (MTMIO), was designed as shown in Scheme 1.

Scheme 1 also shows the reaction between MTMIO and cellulose, which is the same as the reaction between DMDMH/MDMH and cellulose. After the TMIO ring is grafted onto cellulose, the amine bond can be converted to the stable amine halamine, which then will provide the desired durable antibacterial functions. In this article, the synthesis and characterization of MTMIO will be described. The antimicrobial properties and stability of the halamine structures, particularly the durability and rechargeability of the antimicrobial functions after repeated laundering, will also be discussed.

EXPERIMENTAL

Materials

TMIO was provided by the HaloSource Corporation (Seattle, WA). DMDMH was supplied by the Troy Corporation (Florham Park, NJ). Formaldehyde solution (37%), sodium carbonate (anhydrous), hydrochlo-



Scheme 1 Synthesis of MTMIO and chemical modification of cellulose with MTMIO.

ric acid (36%), Triton-100 (anionic penetrating agent), magnesium chloride hexahydrate, and citric acid were purchased from Aldrich (Milwaukee, WI). The cotton fabric samples #400, #423 (twill), #493, and the cotton/polyester blend fabric (65/35) #7409 were purchased from TestFabrics Inc. (West Pittson, PA).

Instruments

FTIR spectra of ungrafted and grafted cotton fabrics were taken on a Nicolet Magana IR-560 spectrometer using sample pellets containing potassium bromide as a reference. The FTIR spectrum of MTMIO was taken by coating the MTMIO sample in chloroform solvent onto a piece of sodium chloride plate. All of the spectra were generated by a transmission mode based on 32 scans with a resolution of 4.0 cm^{-1}. ^{1}H-NMR spectra were recorded on a GE NMR QD-300 spectrometer.

Synthesis of MTMIO

TMIO (14.2 g; 1 mol) was dissolved in 11 mL of 0.1*N* sodium carbonate solution, and the solution was combined with 9 mL (1.1 mol) of formaldehyde (37%). The mixed solution was stirred at 55°C for 2 h, neutralized to pH 7 with 1*N* hydrochloric acid, and cooled to room temperature. After the reaction, the mixture was repeatedly extracted with chloroform, and the extracts were collected and dried under reduced pressure. The final product was a waxy and transparent semisolid, yielding 15.9 g (93%), ^{1}H-NMR (DMSO-d6), δ: 1.08 (6H, —CH_3), 1.26 (6H, —CH_3), 2.23 (1H, NH), 4.64 (2H,—N—CH_2), 5.79 (1H, —OH). FT-IR (cm^{-1}): 1693 cm^{-1}, 2975 cm^{-1}, and 3400 cm^{-1}.

Grafting of MTMIO onto cellulose

A regular wet finishing process, pad-dry-cure, was employed in grafting chemicals to textiles. Fabric samples were immersed in a solution containing MTMIO or DMDMH, magnesium chloride, and anionic wetting agents. The pH value of the finishing solution was adjusted to 4.5–5.5 by citric acid. The fabrics were padded (two dips and two nips) to a desired wet pick-up rate (percentage weight increase on wet fabric). Then they were dried in an oven at 80°C for 5 min and cured at 160°C for 5 min. Finally, the fabrics were machine-washed and tumble dried according to AATCC test method 124, to remove unreacted MTMIO. The weight of the grafted fabric was measured after the fabric was conditioned for over 24 h at 21°C and 65% relative humidity. The add-on of the grafting was calculated according to the following equation:

$$\text{Add-on \%} = [(W_1 - W_0) \times 100]/W_0 \quad (1)$$

where W_0 is the weight of the fabric before grafting and W_1 is the weight of the fabric after grafting.

Chlorination process

The grafted fabric was immersed in a diluted chlorine bleach solution containing a certain amount of active chlorine for about 10 min. The chlorinated fabric was then rinsed twice in water to remove unreacted free chlorine and then air- or tumble-dried. Regeneration of the antimicrobial function of the washed fabric samples was performed under the same conditions.

Testing methods

Antibacterial properties were quantitatively evaluated against *Escherichia coli* (ATCC 2666) and *Staphylococcus aureus* (ATCC 6538) according to AATCC test methods 100.[9] The durability and the rechargeability of the biocidal functions were examined by using a Launder-Ometer (AATCC test method 61) as well as a regular machine (AATCC test method 124). AATCC standard reference detergent 124 was used in the laundry. The fabrics were then tumble- or air-dried. The wrinkle recovery angles (WRA) of the fabrics were evaluated according to AATCC test method 66.

Chlorine analysis

Chlorine concentrations on the fabric samples were determined by using an iodometric titration method. Some of each fabric sample was shredded (0.5 g; weighted to ±0.001 g) and immersed in 15 mL of 0.001*N* sodium thiosulfate solution for about 20 min, to which five drops of 2*N* acetic acid and 30 mL distilled water were added. Then, five drops of 1% starch solution were added as an indicator. The mixture was titrated with a solution of 0.001*N* iodine solution. The amount of active chlorine was calculated according to eq. (2):

$$\text{Active Chlorine (ppm)} = [(15\text{mL } Na_2S_2O_3 - A \text{ mL } I_2) \times 0.001N \times 0.0355 \times 10^6] \div \text{Gram of the fabric} \quad (2)$$

A is the volume of the 0.001*N* I_2 solution used in the titration (mL), and 0.0355 is the milli-equivalent of active chlorine in grams.

RESULTS AND DISCUSSION

Synthesis and characterization of MTMIO

The TMIO ring is unreactive with cellulose, and thus is unable to be grafted onto cellulose directly. How-

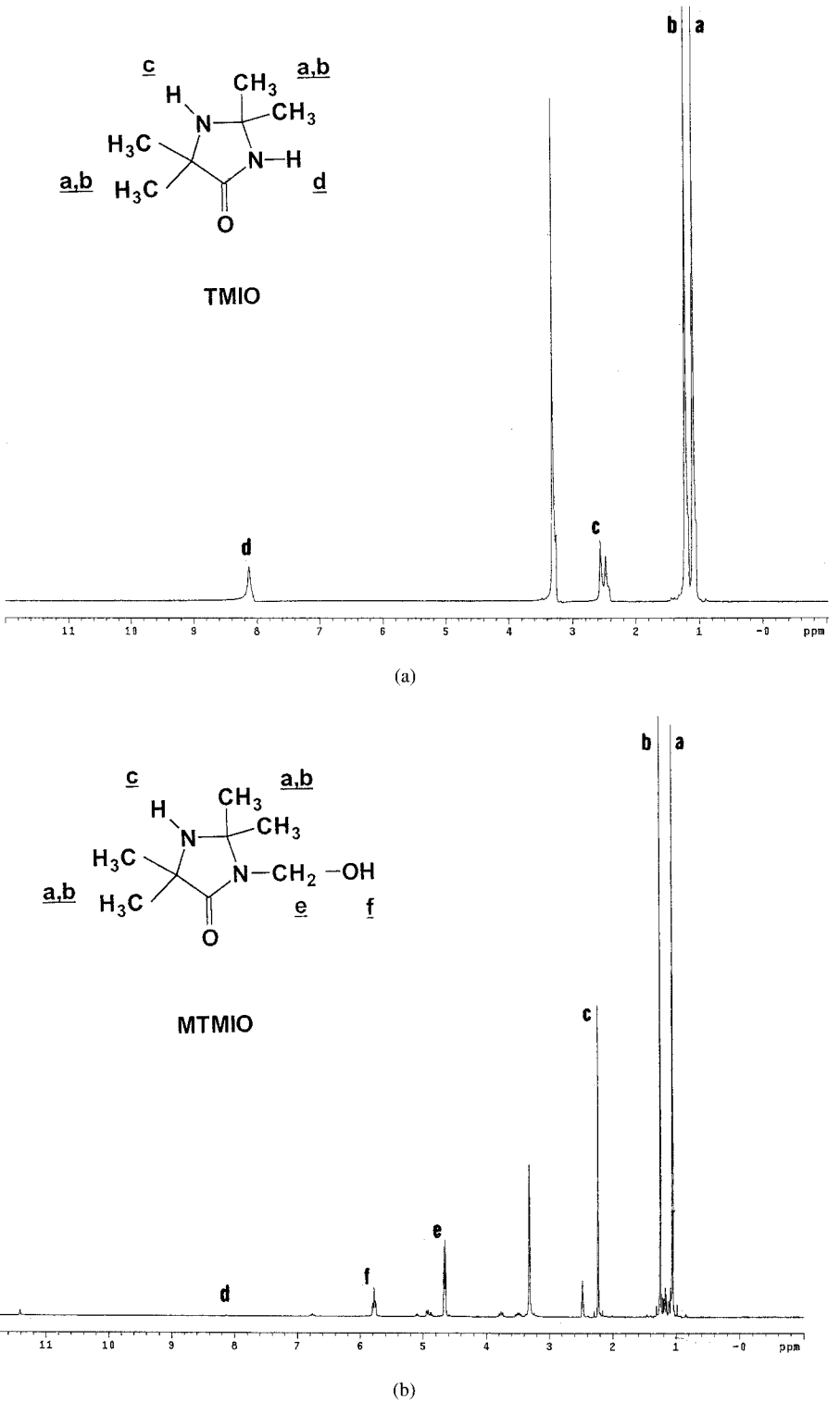


Figure 1 ^{1}H-NMR spectra of TMIO (a) and MTMIO (b).

ever, an introduction of a methylol group, a formaldehyde derivative, to the amide nitrogen of TMIO will make the new compound reactive with cellulose. Although the nitrogen of the secondary amine in the ring should be able to form a methylol group, it rarely happened to TMIO, possibly due to steric hindrance of the four vicinal methyl groups. Thus, the amine nitrogen bond is reserved as a site for chlorination and can be converted to halamine after chlorine bleaching. The structures of MTMIO and TMIO were confirmed by ^{1}H-NMR spectra, shown in Figure 1. The peak (d) at 8.18 ppm (amide proton on TMIO) disappeared, and a

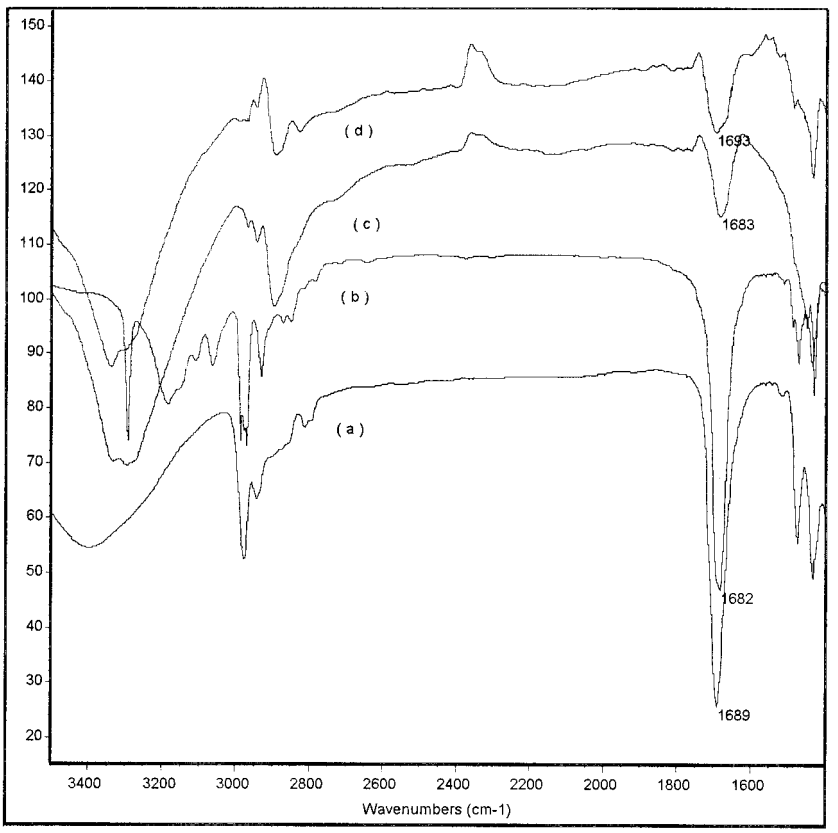


Figure 2 FTIR spectra of MTMIO (a), TMIO (b), subtracted spectrum (c) of the MTMIO modified cotton by the untreated cotton, and subtracted spectrum (d) of chlorine bleached fabrics from untreated cotton.

new peak (e) at 4.64 ppm formed, while the peak (c) only shifted a little, indicating the formation of methylol at the amide bond.

Chemical modification of cellulose fabric

TMIO is grafted onto cellulose by a reaction between MTMIO and the hydroxyl groups on cellulose. The hydroxymethyl groups of MTMIO react with the hydroxyl groups in the cellulose to form the acetal bonds (Scheme 1). Because TMIO has a carbonyl group in the structure, the incorporated TMIO can be identified by FTIR on the modified cellulose (Fig. 2). The curve (c) is a subtracted FTIR spectrum of an MTMIO-treated sample from an untreated one. The new peak of C═O stretching that appears at 1683 cm^{-1} in the spectrum is almost identical to the characteristic band of TMIO (curve b). The same band shifted to 1693 cm^{-1} after chlorination (curve e), an indication of formation of halamine structures.[8–9]

The amounts of grafted TMIO can be reflected from weight increases (add-ons) of fabric samples after the

TABLE II
Antibacterial Efficacy of MTMIO-Treated Fabrics

Concentration of MTMIO	Fabric type	Add-on (%)	Log reduction of *E. coli* at varied contact time					
			10 min	20 min	30 min	60 min	2 h	6 h
1%	400	0.94	<1	1	3	3	4	6
	7409	0.74	<1	1	3	3	4	6
2%	400	1.24	1	3	5	6	6	6
	7409	0.96	<1	1	3	3	4	6
4%	400	1.85	2	5	6	6	6	6
	7409	1.35	<2	4	5	6	6	6
6%	400	2.32	3	6	6	6	6	6
	7409	1.52	2	5	6	6	6	6

Number 400 was a pure cotton fabric and #7409 was a 65/35 polyester/cotton fabric. Bleaching solution contained 200 ppm of active chlorine. Bacteria concentration in the assessment was about 10^6 CFU/mL. Six log reduction means a 99.9999% kill of the bacteria. Wet pick-up rates in the treatments were 100%.

TABLE III
Wrinkle Recover Angles of Fabrics Treated with MTMIO and DMDMH

	Wrinkle recover angle					
	Cotton #493			Cotton twill #423		
	Warp	Filling	W+F	Warp	Filling	W+F
Untreated	101.7	102.7	204.4	89.7	113	202.7
4% MTMIO	102.7	104.7	207.4	91.3	114.7	206
4% DMDMH	131.3	120	251.3	108	121	229

Following AATCC test method 66, wet pick-up rate was 70%. Fabric was dried at 80°C for 5 min and cured at 160–170°C for 5 min; then fabrics were rinsed thoroughly.

treatment, which are shown in Table II. As the concentration of MTMIO in the finishing bath increased six times from 1 to 6%, the add-on rates of the treated fabrics were only raised a little more than twice. Polyester/cotton (65/35) blend fabric (#7409) demonstrated lower add-on rates than the pure cotton (#400) due to lower cellulose content. The reaction yields were obviously lower compared to that of DMDMH, a bireactive compound, on cotton fabrics,[9] but in the same scale to that of MDMH,[7–8] a similar mono-reactive agent. Bireactive compounds secure a high yield due to doubled reactive possibilities from both sites, which may also introduce crosslinking reactions to the polymers.[9] MTMIO can only be grafted onto cellulose and should not result in any crosslinking or wrinkle-free effect to the fabrics. WRAs of the MTMIO-treated cotton fabrics were compared with the results of DMDMH-treated ones, with data listed in Table III. Both MTMIO-treated cotton plain and cotton twill fabrics showed no effect of increasing WRA, because no crosslinking existed. However, the same fabrics treated with DMDMH revealed increased WRA values, clear evidence of crosslinking of cellulosic polymers.[9]

Chlorination of MTMIO-treated fabrics

The biocidal functions of the treated fabrics rely on the amount of halamine bonds formed on the cellulose, which are determined by the amount of TMIO rings and the amount of amine structures that can be chlorinated. The formation of halamine bonds from the cyclic amine depends on the concentration of the active chlorine in the bleaching bath. The high concentration of active chlorine in the bleaching will increase the amount of halamine structures formed on the fabric. Table IV shows the results of active chlorine levels and antimicrobial properties of the finished cotton fabrics bleached with chlorine solutions at different concentrations. The bonded chlorine on finished fabric samples increases with the increase of the active chlorine concentration in the bleaching bath. In addition, within the range of the bath concentrations of 130 to 480 ppm, all the fabric samples gave 6-log reductions at the contact times of both 30 and 60 min.

The grafted imidozalidinone rings on cellulose can only provide amine N—H bonds, which are then converted to the very stable amine halamine structure by chlorine bleaching. The amount of amine halamine affects the antimicrobial efficacy. As the finishing concentrations of MTMIO changed from 1 to 6%, biocidal power of the fabrics increased, revealed by the antibacterial speed against *E. coli*, a representative Gram-negative bacterium (Table II). Both cotton and polyester/cotton blend fabrics exhibited complete microbial reduction (6 log) within a reasonable contact period, even at the bath concentration as low as 1%, but significantly slower in speed than that of DMDMH- and MDMH-treated ones. For example, at an add-on rate of TMIO around 1%, the treated fabric needed a contact time of 6 h to provide a complete kill of 10^6 CFU/mL of *E. coli* (6 log reduction), while DMDMH- and MDMH-treated fabrics only took less than 2 min to provide the same scale of kill.[9] This is completely

TABLE IV
Chlorination of Treated Fabrics with Different Concentrations of Active Chlorine

Fabric type	Add-on (%)	[Cl] (ppm) in bath	[Cl] (ppm) on fabric	Log reduction	
				30 min	60 min
Cotton #493	1.02	130	684	6 log	6 log
		330	897	6 log	6 log
		480	1002	6 log	6 log
Cotton twill #423	1.67	130	688	6 log	6 log
		330	970	6 log	6 log
		480	1114	6 log	6 log

[a]Finishing conditions were the same as Table III.

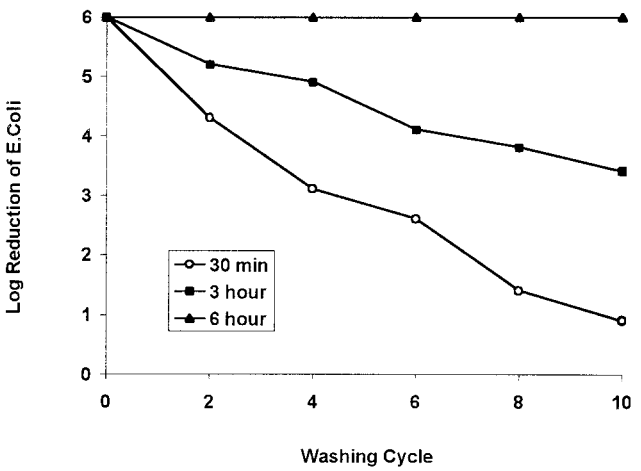


Figure 3 Washing durability of antimicrobial functions.

consistent with the biocidal results of related amine halamine compounds.[11] Amine halamine has the highest stability among three halamine structures, and thus the weakest reactivity against bacterial cells, resulting in a slow kill. Fabric samples containing amine halamines would take longer contact time to inactivate bacteria by going through any of the biocidal reactions, oxidative or chlorine exchange.[17] When the add-on rate increased to 2%, the minimum contact time to result in a 6 log kill was shortened to about 30 min, still slower than the products that resulted from hydantoin derivatives. The difference is that both DMDMH- and MDMH-treated fabrics contain exclusively imide and amide halamine structures that are more lethal to microorganisms.

Improved durability of biocidal functions

Based on the data shown in Table I, amine halamines hydrolyze in water at a much slower speed than imide or amide halamines. The grafted TMIO rings only bring in amine bonds to cellulose, which then form stable amine halamines after chlorination. Due to the stability of the amine halamine in water, the treated fabrics could show improved durability of the antimicrobial functions against repeated laundering. The loss of active chlorine in laundry is mostly caused by hydrolysis of the halamine bonds in water, particularly accelerated by the existence of surfactants and high pH level, and could be reflected by the decrease of antimicrobial performance after repeated washing. The antimicrobial performance of the fabrics can be evaluated from either the contact time, to provide a complete kill of 10^6 CFU of bacteria, or a reduction rate at a constant contact time. Figure 3 shows the change of log reduction of the MTMIO-treated cotton fabrics after up to 10 cycles of washing in a Launder-Ometer. The changes of log reductions of *E. coli* varied according to the different contact times (30 min, 3 h, and 6 h). The fabrics could not provide complete kills to the microorganisms under short contact times, but under a longer contact time such as 6 h, the fabrics could provide a complete kill. The prolonged contact time to result in a complete inactivation of the bacterium is caused by migration time of active chlorine that is not in contact with bacterial cells transferring from halamine to their precursors (equations in Table I). More stable halamine structures inside polymers are more difficult to dissociate chlorine, and thus need longer time to replenish lost active chlorine outside of the polymers.

Table V shows the results of chlorine loss of MTMIO- and DMDMH-treated fabrics and their biocidal effects against *E. coli* and *S. aureus*, respectively, after two and five times continuous laundering without rebleaching. Chlorine losses of MTMIO-treated samples were lower than those of DMDMH-treated ones, again due to the different stability of halamine structures, which then contributes to the different antimicrobial functions. Even after five machine washes, the amine halamine structures still provided the desired antimicrobial functions, while the imide or amide halamines lost 70–80% of the original power and had to be recharged before reuse. Furthermore, the amine

TABLE V
Chlorine Loss and Antimicrobial Effect of MTMIO- and DMDMH-Modified Samples

		Testing with *E. coli*			Testing with *S. aureus*		
Chemical	Washing cycle	Cl (ppm)	Cl loss (%)	Log reduction	Cl (ppm)	Cl loss (%)	Log reduction
MTMIO	0	565	-	6	654	-	6
	2	507	10.2	5	616	6.1	6
	5	498	11.9	4	601	8.4	4
DMDMH	0	863	-	6	934	-	6
	2	218	74.7	1.5	380	59.3	3
	5	157	81	0.9	274	70.7	2

For pure cotton fabric #493, the total finishing bath concentration was 4% and wet pick-up was 70%. Concentrations of bacteria: *E. coli* 5×10^6 CFU/mL and *S. aureus* 7×10^6 CFU/mL. 6 Log reduction is equivalent to 99.9999% kill. Contact time was 60 min. Machine-washing was according to AATCC standard test method 124-1999. Tests 1 and 2: The DMDMH and MTMIO-treated fabrics were bleached separately with the same concentration of active chlorine (150 ppm).

TABLE VI
Changes of Antibacterial Function of MTMIO (4%)-Treated Fabrics after Storage of 6 Months

	Log reduction against *E. coli*			
	Cotton fabric #400		Polyester/cotton fabric #7409	
Storage time (month)	30 min contact	2 h contact	30 min contact	2 h contact
0	6 log	6 log	6 log	6 log
6	4 log	6 log	2 log	4 log
Rebleaching	6 log	6 log	6 log	6 log

Fabrics were stored in plastic bags.

halamine could inactivate both Gram- positive and -negative bacteria effectively. It should be pointed out that the lost active chlorine and antimicrobial functions on the fabrics could be fully recharged in chlorine bleaching.

Stability of halamine structure in storage tests

N-halamine structures are active sites that can interact with both microorganisms and environmental factors such as moisture, and the latter interactions may affect shelf lives of the halamine products. The moisture in the air is quite detrimental to halamine structures because it can induce the hydrolysis of halamine bonds and thus damage the antimicrobial functions. Stable halamine structures should improve the resistance to the environmental factors and therefore they can be stored for a longer duration. Table VI shows the reduction of antimicrobial functions of the MTMIO finished cotton and polyester/cotton fabrics after being stored for 6 months in sealed plastic bags. Although a decrease of the log reduction was found at the end of the storage, the two fabric samples still demonstrated certain antimicrobial properties. Furthermore, additional chlorine bleaching could fully recover the lost functions. This indicates that the loss of the functions is mainly caused by the reduction of halamine bonds, not the connection between TMIO rings and cellulose.

CONCLUSIONS

A new biocidal precursor MTMIO was synthesized and grafted onto cellulose by a wet textile finishing process. The grafted TMIO rings can be converted to amine halamines by using a simple chlorine bleaching process. The amine halamines were proven to be more stable than imide halamines on the treated fabrics, similar to the results obtained on other halamine compounds. This outstanding stability of the amine halamines could be evidenced by a slower but more durable biocidal effect against bacteria and the improved washing fastness of the biocidal functions compared with the properties of the fabrics treated with DMDMH. The halamine structures survived 10 times of repeated Launder-Ometer washing and could be recharged with a diluted chlorine bleaching, similar to other halamine structures. Due to the additional stability of the amine halamines, MTMIO-treated fabrics are more suitable for apparel and hygienic uses.

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