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Amphiphilic Silicone Architectures via Anaerobic Thiol–Ene Chemistry

Daniel J. Keddie,[†] John B. Grande,[‡] Ferdinand Gonzaga,[‡] Michael A. Brook,[*,‡] and Tim R. Dargaville[*,†]

Institute of Health and Biomedical Innovation, Queensland University of Technology, 60 Musk Ave, Kelvin Grove, Queensland, Australia 4059, and Department of Chemistry and Chemical Biology, McMaster University, 1280 Main Street West, Hamilton, Ontario, Canada L8S 4M1

t.dargaville@qut.edu.au; mabrook@mcmaster.ca

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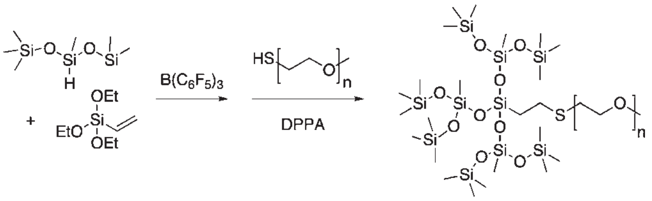
ABSTRACT



Despite broad application, few silicone-based surfactants of known structure or, therefore, surfactancy have been prepared because of an absence of selective routes and instability of silicones to acid and base. Herein the synthesis of a library of explicit silicone-poly(ethylene glycol) (PEG) materials is reported. Pure silicone fragments were generated by the $B(C_6F_5)_3$-catalyzed condensation of alkoxysilanes and vinyl-functionalized hydrosilanes. The resulting pure products were coupled to thiol-terminated PEG materials using photogenerated radicals under anaerobic conditions.

Silicone surfactants (e.g., Figure 1A) are usually based on the poly(ethylene glycol) (PEG) modification of short-chain silicones[1,2] or of long-chain polymers modified randomly along the backbone.[3−6] While such compounds are considered “exotic” in the surfactant world, due both to price and composition, the compounds are essential in certain applications, including cosmetics, paints, and coatings and for the stabilization of bubbles in polyurethane foam structures.[7]

Like most silicones, silicone surfactants are comprised of complex mixtures of compounds[8−11] that can vary significantly in polydispersity index and, therefore, surfactancy. Normally, the compounds are prepared by grafting to an existing hydrosilane an allyl-terminated PEG chain using platinum-catalyzed hydrosilylation ($PEG\text{-}CH_2CH{=}CH_2 + HSiR_3 \rightarrow PEG(CH_2)_3SiR_3$). While the reaction is extremely efficient—in ideal cases, less than 10 ppm of Pt is required—platinum is expensive. In addition, two regioisomers are often generated in the hydrosilylation process. Worse, with the exception of only a very few low molecular weight materials as shown in Figure 1B, well-defined hydridosilicones are simply not available. Larger molecular weight silicone surfactants are sold as broad molecular weight mixtures of molecules bearing varying degrees of functionalization. There is, as a consequence, no general

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[†] Queensland University of Technology.

[‡] McMaster University.

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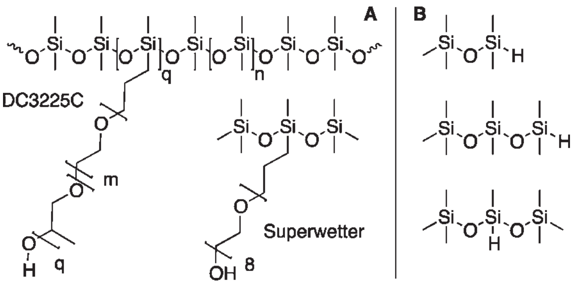


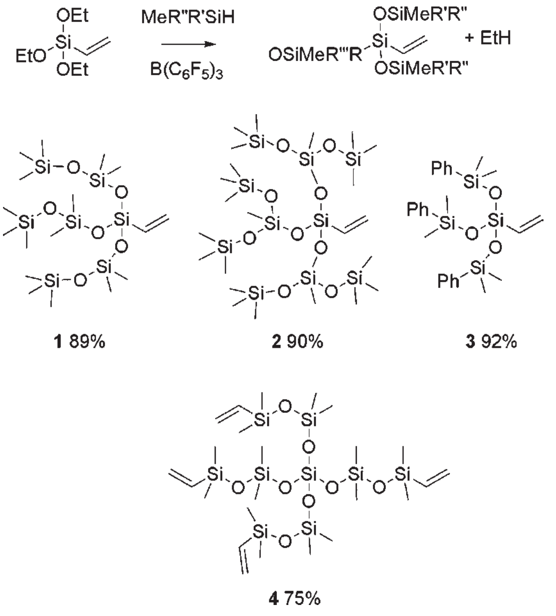
Figure 1. Structures of (A) representataive, commercially available silicone surfactants and (B) readily available functional hydrosiloxanes.

route to structurally well-defined silicone surfactants and little knowledge about structure activity relationships.[12]

Further complicating the situation is the intrinsic reactivity of silicone polymers. Either acids or bases can initiate a process in which silicones depolymerize in an equilibrium between chains and rings, for which the equilibrium constant is approximately 1.[13] Any processes that involve linking hydrophiles to well-defined silicones must therefore avoid both acidic and basic conditions.

Recently, we described a simple route to explicit, medium sized silicone structures,[14] including functional silicones,[15] that involves the $B(C_6F_5)_3$-catalyzed condensation of hydrosilanes and alkoxysilanes to give silicones and alkane byproducts (the Piers–Rubinsztajn reaction[16] (Scheme 1)). The utilization of this route for the creation of structurally well-defined silicone amphiphiles could avoid the disadvantages of platinum-catalyzed processes and, in addition, would allow one to probe structure–surface activity relationships of the surfactants formed.

Scheme 1. Using the Piers–Rubinsztajn Reaction To Prepare Explicit Vinylsiloxanes



Four different explicit silicones were produced using the Piers–Rubinsztajn coupling of alkoxy- and hydrosilanes (Scheme 1).[16] Catalysis by $B(C_6F_5)_3$ of the condensation of vinyltriethoxysilane and the pentamethyldisiloxane, 1,1,1,3,5,5,5-heptamethyltrisiloxane, or phenyldimethylsilane, respectively, led to siloxanes **1**, **2**, and **3** in good yield. Alternatively, the tetravinyl material **4** could be made in an analogous process with $Si(OEt)_4$. These and a commercial silicone terminated with vinyl groups served as substrates for the thiol–ene reaction (Scheme 1).

The Piers–Rubinsztajn approach constitutes one part of the synthesis of well-defined surfactants. We sought a simple and efficient route for grafting these silicones to hydrophiles under conditions that do not affect silicone architecture: that is, under conditions that are neither acidic nor basic.[17] Several strategies presented themselves including the modular, metal free "click" reaction between azides and alkynes.[18] We reasoned that a thiol–ene "click" process[19,20] which has been broadly exploited in many technical areas,[21] including silicones,[22] should efficiently produce a wide range of molecular structures that can be isolated with limited workup. Therefore, we examined and describe below the synthesis of a library of amphiphilic silicones using thiol–ene chemistry, initiated by photolysis of 2,2-dimethoxy-2-phenylacetophenone (DMPA), between PEG thiols and well-defined silicone architectures, prepared by boron-catalyzed coupling of lower alkoxy- and hydrosiloxanes.

A series of PEG oligomers, terminated at a single end by thiols, was synthesized from the corresponding PEG monomethyl ethers in three steps (see Scheme 2). Synthesis of the PEG tosylates from the alcohol using the procedure previously reported by Keegstra et al.[23] proved facile and gave products **5**–**8** in high yield (88–91%) without the need for purification. Initial attempts to form the PEG thioacetates **9**–**12** directly, by refluxing the tosylates in dry MeOH[24] in the presence of KSAc, did not produce the desired

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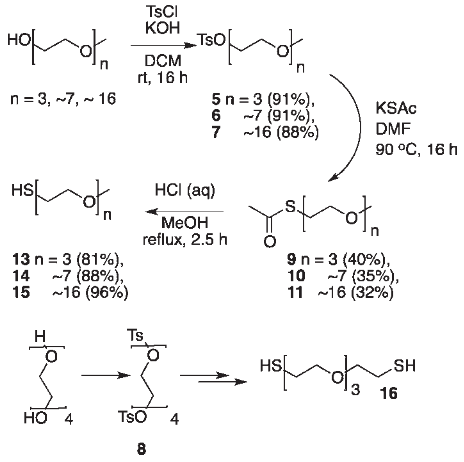
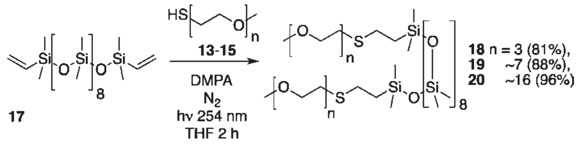
Scheme 2. Synthesis of PEG Thiols



Scheme 3. Thiol–Ene Coupling of PEG Thiols with Divinyl PDMS[a]



[a] DMPA = 2,2-dimethoxy-2-phenylacetophenone.

products. After the solvent was changed to dry DMF,[25] however, the PEG thioacetates **9**–**12** could be isolated in moderate yield (32–40%). Subsequent acid hydrolysis of the thioesters using 10% aq HCl/MeOH furnished the target PEG thiols **13**–**16** in high yield (81–96%). Note that the low polydispersity of the original PEG was preserved in the products. For compounds **14** and **15**, for example, the average PEG oligomer values of 7 ± 1 and 16 ± 4, respectively, are also reflected in the mass spectra of the subsequent silicone product following the thiol–ene process (see below): high resolution mass spectra confirm the structure of the compound with 7 or 16 PEG units, respectively (Supporting Information for compounds **22**, **28** and **31**), and low resolution mass spectra of both the PEG-thiol and thioether product show the same distributions of oligomers, separated by 44 mass units.

Initial coupling reactions between discrete vinyl-functional siloxanes and alkyl thiols, such as undecanethiol and thioglycerol, under aerobic conditions based on the methodology reported by Campos et al.,[26] gave the desired products within 30 min under UV irradiation (data not

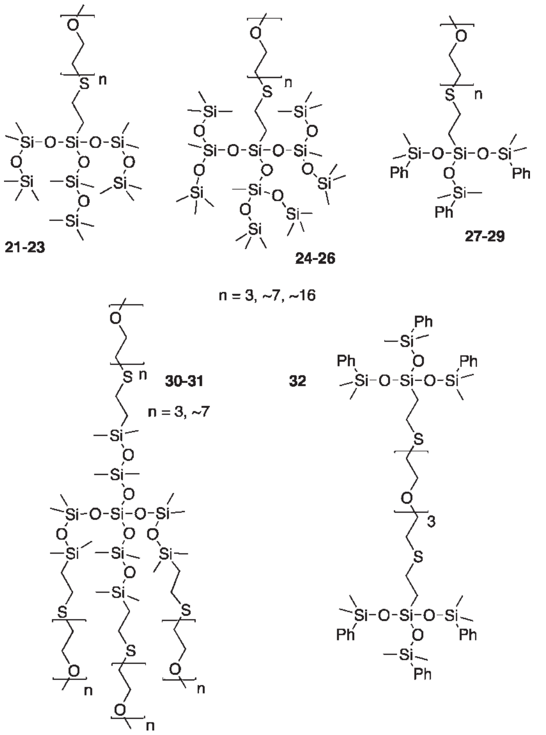
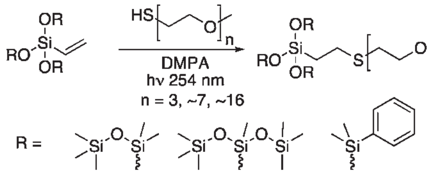
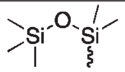
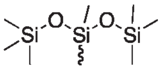
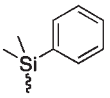


Figure 2. Explicit PEG–silicone surfactants.

Table 1. Silicone–PEG Compounds



starting silicone	R (scheme above)	PEG-thiol (n)	product	yield (%)[a]
1		**13 (3)**	**21**	71
		14 (~7)	**22**	78
		15 (~16)	**23**	81
2		**13 (3)**	**24**	91
		14 (~7)	**25**	87
		15 (~16)	**26**	82
3		**13 (3)**	**27**	95
		14 (~7)	**28**	89
		15 (~16)	**29**	84
4	Figure 2	**13 (3)**	**30**	82
		14 (~7)	**31**	72
3		[b]	**32**	89

[a] Isolated yield. [b] Tetraethyleneglycol dithiol.

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shown). This was not surprising, as, the literature indicates that the thiol–ene reaction should not be significantly hindered by the presence of oxygen.[27] However, thiol–ene reactions with silicones are, apparently, not as pliable.[28] Survey experiments with a commercially available α,ω-divinyl PDMS **17** failed to lead to any products in the presence of oxygen after 2 h irradiation but, after degassing and reirradiation, the desired ABA block copolymers **18**–**20** formed in high yield (66–79%) within 1 h as shown by NMR (Scheme 3): single regioisomers were observed. The stoichiometry used for this reaction was a 1:1.5 ratio of thiol to vinyl group to ensure complete conversion of the PEG-thiol, except for high molecular weight materials where a 1:1 ratio was used to eliminate the need to separate the polar unreacted PEG from the synthesized amphiphiles. When an excess of the PEG thiol was used (1.5 equiv thiol per vinyl group), the resulting products were difficult to separate from the excess starting material, especially when the larger PEG compounds were used (Scheme 3).

Analogous reaction conditions were used to convert vinyl-functional silicones **1**–**3** into surface active silicones **21**–**29** using 3 PEG thiols **13**–**15** (Table 1, Figure 2). It was also possible to prepare the star-shaped silicones **30** and **31** from **4** and the bola-amphiphile **32** from tetraethyleneglycol dithiol **16** (Figure 2). The explicit silicone fragments were incorporated into the products unaltered, without the competing metathesis that accompanies acid or basic conditions. The formation of both the PEG-thiols and thioether reactions were in lower than expected yields for such reactions. This is a consequence of our desire to have absolutely pure materials, which will permit an understanding of structure/surface activity relationships. Several columns were required in the former case, and use of narrow distillation cuts in the latter case favored purity over yield of these polar molecules.

Low concentrations of $B(C_6F_5)_3$ facilitate the condensation of alkoxy- and hydridosilanes to give siloxane bonds under conditions that do not initiate the metathesis of the silicone: explicit structures can be prepared *and isolated.* Silicone compounds, with various 3D profiles—including linear, branched, or star—are thus readily available from simple starting materials. The elaboration of these compounds into hydrophilically modified materials can also be performed without degrading the silicone structures by the regioselective, photoinduced thiol–ene click reaction of thiol-terminated PEG oligomers of various molecular weights; we have described explicit structures, with different three-dimensional profiles, of molecular weights ranging from about 1200 to about 3300 g mol^{-1}. Preliminary studies demonstrate that the products, particularly as the relative PEG fraction increases, are both soluble and stable in water. Such compounds are expected to have precise and predictable surface properties that depend upon their 3D structure and the ratio of hydrophilic to hydrophobic moieties, which will be the subject of future reports.

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Supporting Information Available. Experimental protocols, ^{1}H and ^{13}C NMR, HRMS spectral data for compounds **21**–**32**, and LRMS for **22**, **28**, and **31**. This material is available free of charge via the Internet at http://pubs.acs.org.

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