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Polyoxazoline-Based Bottlebrush and Brush-Arm Star Polymers via ROMP: Syntheses and Applications as Organic Radical Contrast Agents

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Abstract

The synthesis of functional poly(2-alkyl-2-oxazoline) (PAOx) copolymers with complex nanoarchitectures using a graft-through ring-opening metathesis polymerization (ROMP) approach is described. First, well-defined norbornene-terminated poly(2-ethyl-2-oxazoline) (PEtOx) macromonomers (MM) were prepared by cationic ringopening polymerization. ROMP of these MMs produced bottlebrush copolymers with PEtOx side chains. In addition, PEtOx-based branched MMs bearing a terminal alkyne group were prepared and conjugated to an azide-containing bis-spirocyclohexyl nitroxide via Cu-catalyzed azide-alkyne cycloaddition (CuAAC). ROMP of this branched MM, followed by in situ cross-linking, provided PEtOx-based brush-arm star polymers (BASPs) with nitroxide radicals localized at the core-shell interface. These PEtOx-

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Supporting Information

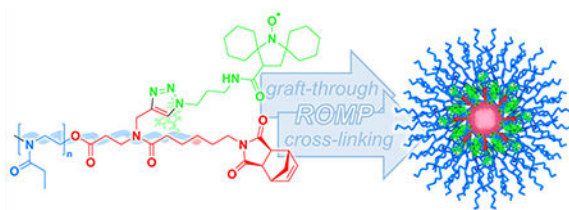
The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acsmacrolett.9b00016.

Materials, instrumentation, experimental procedures, NMR and mass spectra, additional SEC traces and EPR spectra with fitting data (PDF).

The authors declare no competing financial interest.

based nitroxide-containing BASPs displayed relaxivity values on par with state-of-the-art polyethylene glycol (PEG)-based nitroxide materials, making them promising as organic radical contrast agents for metal-free magnetic resonance imaging (MRI).

Graphical Abstract



Particular members of the poly(2-alkyl/aryl-2-oxazoline) (PAOx) class of polymers, for example, poly(2-(*m*)ethyl-2-oxazoline)s,^{1,2} have garnered increasing interest in the biomedical field. The unique properties of PAOx, such as biocompatibility and stealth behavior, make them potential alternatives to polyethylene glycol (PEG), the gold standard polymer for biomedical applications.^{3,4} Questions regarding the potential immunogenicity of PEG^{5,6} and its degradation modes^{7,8} have motivated the search for polymers that could serve as substitutes or complements. Among the many polymers studied in this context, which include poly(oligo-(ethylene glycol) methyl ether methacrylate),^{9–11} poly(*N*-(2-hydroxypropyl)methacrylamide),¹² polysarcosine,¹³ polyvinylpyrrolidone,¹⁴ poly(*N*-acryloylmorpholine),¹¹ and polyzwitterions,^{15,16} PAOx have shown some of the most promising results, with a drug conjugate to treat Parkinson's disease currently in clinical trials.¹⁷

PAOx are synthesized by cationic ring-opening polymerization (CROP). Chemical and physical versatility is provided by variation of the side chain of the requisite 2-alkyl/aryl-2-oxazoline monomers, as well as by the use of suitable initiators and terminators for chain-end functionalization.^{18–21} Notably, end-capping with appropriately designed terminators enables facile introduction of functional groups that would otherwise be incompatible with CROP. Moreover, end-capping with species such as styrenics,^{22–25} acrylates,^{26–30} and methacrylates^{27,30–32} provides macromonomers (MM) that can be used to form graft and comb-like copolymers in subsequent graft-through polymerizations. For instance, RAFT copolymerization of methyl methacrylate and an ω -methacrylated poly(2-ethyl-2-oxazoline) (PEtOx) MM afforded pH- and temperature-responsive graft copolymers.³¹ Nonetheless, attempts to prepare PEtOx-based bottlebrush polymers (BBPs) via free radical, RAFT, or nitroxide-mediated polymerizations revealed a steric crowding effect, preventing the formation of BBPs with degrees of polymerization (DP) > 25.²⁹

Graft-through ring-opening metathesis polymerization (ROMP) has been applied to the synthesis of a wide range of polymeric architectures including bottlebrush and dendronized polymers.^{33–39} ROMP of norbornene-functionalized MMs using ruthenium initiators is particularly suited for the synthesis of side-chain functional polymers with controllable molar masses and low dispersities.^{12,39–42} Cross-linking of living BBPs results in another unique nanoarchitecture: the brush-arm star polymer (BASP).⁴³ BASPs feature a dense

unimolecular micelle-like structure, with tunable core and shell functionalities that may consist of a variety of polymer compositions, as well as therapeutic payloads or imaging agents covalently bound at the core-shell interface. Such features have been exploited to afford two- and three-miktoarm^{44,45} as well as PEG-based⁴⁶ BASPs with promising properties for drug delivery and imaging applications, including magnetic resonance imaging (MRI) and near-infrared fluorescence (NIRF) imaging.^{43,47}

To date, BBPs and BASPs intended for biomedical applications have primarily been derived from norbornene-terminated PEG MMs. Given the significant interest in PAOx as alternatives to PEG, we sought to investigate the properties of PAOx-based BBPs and BASPs synthesized via graft-through ROMP. Herein, we present the design and synthesis of ROMP-compatible PAOx-based MMs (Scheme 1A). Specifically, termination of growing PEtOx chains with a norborneneacid (**X**) or a norbornene-alkyne-acid (**Y**) afforded linear and bivalent MMs **MM1** and **MM2**, respectively. We demonstrate the efficient synthesis of BBPs from **MM1** using ROMP (Scheme 1B). In addition, **MM2** was conjugated to an azide-containing bis-spirocyclohexyl nitroxide (**N₃-chex**) via coppercatalyzed azide-alkyne cycloaddition (CuAAC) to produce **MM3**, which was subsequently used for the synthesis of PEtOx-based BASP organic-radical contrast agents (BASP-ORCAs; Scheme 1C) that could serve as alternatives to metal-containing MRI contrast agents and to previously reported PEG-based ORCAs.⁴⁷⁻⁵⁰

PEtOx was prepared following previously reported optimal conditions (microwave irradiation at 140 °C in acetonitrile),⁵¹ with methyl tosylate as the initiator and a monomer-to-initiator ratio of 30. The polymerization was terminated by addition of either **X** or **Y**, providing **MM1** or **MM2**, respectively (Scheme 1, see Supporting Information for details). Size-exclusion chromatography (SEC) traces of both MMs showed a monomodal molar mass distribution with $\text{MWD} < 1.2$ (Figures 1 and S7). The successful end-functionalization of both MMs was confirmed by matrix-assisted laser desorption/ionization time-of-flight (MALDI-ToF) mass spectrometry. The spectra showed a major species with the targeted mass:charge ratio, that is, with methyl and norbornene-based groups as the α and ω chain ends, respectively (Figures S1 and S2). A second population of lower intensity was observed in both spectra; it could be assigned to proton-initiated PEtOx, potentially arising from trace water or chain transfer.⁵²⁻⁵⁴ Nevertheless, the norbornene group is present in both species, making them suitable for ROMP. ¹H NMR further confirmed the presence of the desired end-groups (Figures S3 and S4). The integration values for the end-group signals of each MM, at 2.9 ppm for the α methyl group and at 6.2 ppm for the ω norbornene olefin, slightly differed from the theoretical 3:2 ratio due to the presence of the aforementioned proton-initiated polymer chains. Number-average molar mass values calculated from ¹H NMR (M_n ,NMR) by ω end-group analysis were 2700 and 3080 g mol⁻¹ for **MM1** and **MM2**, respectively. These values are in close agreement with the expected values. Table S1 provides a summary of the characterization data for these MMs.

Next, we investigated ROMP of these PEtOx MMs. First, **MM1** was dissolved in THF and exposed to Grubbs 3rd-generation bispyridyl complex (**G3**) at a MM/**G3** ratio (i.e., targeted degree of polymerization, DP_{theo}) of 10:1 at room temperature. Samples of the reaction were quenched at predetermined time points by addition of excess ethyl vinyl ether (EVE). SEC

analysis revealed that full conversion was achieved within 10 min (Figure S8). **PEtOx** BBPs with varying DP_{theo} (10, 25, and 50) were prepared, and SEC analyses showed high conversion in all cases, with the expected $M_{n,\text{SEC}}$ increase and $\text{PDI} < 1.2$ (Figure 1). Further characterization by ^1H NMR (Figure S9) shows the characteristic **PEtOx** signals (3.4, 2.3, and 1.05 ppm) and the appearance of signals from the polynorbornene olefin backbone (5.5 and 5.8 ppm), while the norbornene alkene signal from **MM1** (6.2 ppm) is no longer visible.

After successful ROMP of linear **MM1**, we investigated the synthesis of functional polymers derived from bivalent **MM2**, which features a **PEtOx** chain and a pendant alkyne for the conjugation of an azide of interest by CuAAC.⁵⁵ As opposed to copolymerization of two monomers, the use of bivalent MMs ensures that exactly one of each side chain group (e.g., polymer and azide of interest) is attached onto each repeating unit of the resulting BBP. It also sets the location of the smaller group (in this case, the azide) within the core of the BBP architecture.⁵⁶ To illustrate this concept, we conjugated an azide-functionalized spirocyclohexyl nitroxide (**N₃-chex**, Scheme 1) to **MM2** by CuAAC, thus providing **MM3**. **MM3** was characterized using MALDI-ToF MS, SEC, and electron paramagnetic resonance (EPR) spectroscopy. The SEC traces confirmed that the structure of the polymer backbone after the CuAAC reaction remains unchanged, conserving its narrow molar mass distribution ($\text{PDI} = 1.13$; Figure S7). MALDI-ToF MS validated the quantitative functionalization of **MM2**, with the main population observed having identical theoretical and experimental m/z values (Figure S5). These findings were further corroborated by EPR (Figure 3A, vide infra), where the measured spin concentration was $>95\%$.

PEGylated dendrimers, bottlebrush polymers, and BASPs carrying chex have been used as redox probes and highly sensitive ORCAs for MRI.^{47,57–59} In particular, PEGylated BASP-ORCAs featuring chex have exceptionally high transverse relaxivities that enable T_2 -weighted tumor imaging in vivo.⁵⁸ Here, we sought to prepare **PEtOx**-based BASP-ORCAs for comparison to our previously reported PEGylated BASP-ORCAs. Following the brush-first ROMP approach,⁴³ **MM3** (7 or 10 equiv) was exposed to **G3** (1 equiv) for 30 min to yield living BBPs with $DP_{\text{theo}} = 7$ or 10, respectively. Then, $N = 20$ or 30 equiv of bisnorbornene acetal cross-linker (**AcetalXL**) were added, and the mixtures were allowed to react for 6 h while stirring. Following quenching with EVE, the samples were characterized by NMR and SEC. ^1H NMR shows the relevant **PEtOx** signals (3.4, 2.3, and 1.05 ppm) and the absence of the norbornene alkene signal from **MM3** (6.2 ppm) after the formation of **BBP1** and the respective **BASPs** (Figure S10). SEC analysis revealed good conversion for both the MM-to-BBP and the BBP-to-BASP steps (Figure 2). The $M_{n,\text{SEC}}$ values for the $N = 20$ BASPs with $DP_{\text{theo}} = 7$ or 10 were similar (5.9 or $5.0 \times 10^5 \text{ g mol}^{-1}$, respectively). Conversely, by keeping the BBP DP_{theo} constant (i.e., 7), but increasing N from 20 to 30, the $M_{n,\text{SEC}}$ underwent an approximately 2-fold increase (5.9 to $10.8 \times 10^5 \text{ g mol}^{-1}$), showcasing the influence of N on the size of the resulting BASPs. This trend was further confirmed by dynamic light scattering (DLS) and transmission electron microscopy (TEM, Figure S11), where the largest BASP diameter ($D_{h,\text{DLS}} = 27 \pm 9 \text{ nm}$, $D_{\text{TEM}} = 54 \pm 10 \text{ nm}$) was observed for $N = 30$, compared to its $N = 20$ BASP analogue ($D_{h,\text{DLS}} = 21 \pm 6 \text{ nm}$, $D_{\text{TEM}} = 47 \pm 7 \text{ nm}$; Figure 3C). It should be noted that the larger D_{TEM} compared to $D_{h,\text{DLS}}$ is due to aggregation of the BASPs during TEM sample preparation.

EPR was used to confirm and quantify the presence of chex in these polymers. The normalized EPR spectra for **MM3**, its corresponding $DP_{\text{theo}} = 10$ BBP, and three different BASP-ORCAs are shown in Figure 3A. Consistent with previous reports,^{47,57,58} the peaks in the spectra for BBPs and BASP-ORCAs are significantly broadened compared to those for the MM precursor. Computational analyses of these spectra reveal that the fast-moving nitroxide radicals of **MM3** are restricted in motion near the polynorbornene backbone of the BBP and BASP-ORCAs (Figure S12). For BASP-ORCAs, the signal broadening is more apparent due to the drastically reduced freedom of motion of the nitroxides, as these are trapped near the rigid core of the BASP. These results are similar to what was reported for PEG-based BASP-ORCAs.^{47,57,58} In all cases, the measured spin concentrations were very high (>85%).

To evaluate the potential of these polymers as metal-free MRI contrast agents, their longitudinal (r_1) and transverse (r_2) relaxivities were measured by collecting phantom images (Figure 3B) at various polymer concentrations using a 7 T MRI scanner. The paramagnetic nitroxide radicals provide MRI contrast by shortening the longitudinal (T_1) and transverse (T_2) relaxation times of neighboring water molecules. The per nitroxide r_1 values obtained for this family of polymers ranged from 0.14 to 0.19 $\text{mM}^{-1} \text{s}^{-1}$, showing minimal variation when the polymer architecture was changed from **MM3** (0.14 $\text{mM}^{-1} \text{s}^{-1}$) to BBP and BASP (Figure 3C). Nevertheless, r_2 underwent a significant increase from 0.17 (for **MM3**) to 0.58 (for **BBP1**) and further rose to 1.83–2.28 $\text{mM}^{-1} \text{s}^{-1}$ for the BASPs, with the largest r_2 observed for the BASP synthesized using $N = 30$. This large r_2 value leads to significant darkening (i.e., negative contrast) of phantom images of the BASP-ORCA solutions compared to **MM3** and **BBP1** (Figure 3B). Compared to the common model nitroxide 3-carbamoyl-PROXYL (3-CP), the r_2 values obtained from the PEtOx-based BASPs are 11–13.5 larger⁴⁷ and are up to 7.5-fold larger than a recently reported polyurethane-based ORCA.⁶⁰ Nevertheless, these values are still below those of analogous PEG-based BASP-ORCAs (4.67 $\text{mM}^{-1} \text{s}^{-1}$).⁴⁷ Apart from the absolute relaxivity, the r_2/r_1 ratio is also crucial for achieving optimal T_2 -weighted MRI contrast.⁶¹ Notably, the r_2/r_1 ratios of the PEtOx-based BASPs are comparable to those of reported PEG-based BASP-ORCAs. Further screening of parameters such as BBP DP_{theo} and cross-linker equivalents N could potentially positively impact their relaxivities. Nevertheless, the results reported here already make PEtOx-based BASPs competitive with PEG-based BASPs, the latter of which have the highest-known r_2 values for organic contrast agents, and should motivate their further investigation in vivo.

In this work, a versatile approach for the synthesis of functional PEtOx-based polymers with complex nanoarchitectures by ROMP is described. Novel norbornene-terminated PEtOx MMs were designed by exploiting the termination step of CROP. ROMP of these MMs led to a variety of well-defined BBPs, with the possibility to introduce functionalities by using bivalent MMs and CuAAC. This strategy allowed the formation of BASPs containing stable chex nitroxides that can potentially be used as ORCAs for MRI. The evaluation of the magnetic properties of these structures showed relaxivity values far exceeding those of model nitroxides and polyurethane-based ORCAs. These results show the suitability of our

PEtOx-based BASP-ORCAs as metal-free MRI contrast agents and their potential for further development as an alternative to the previously reported PEG-based MRI probes.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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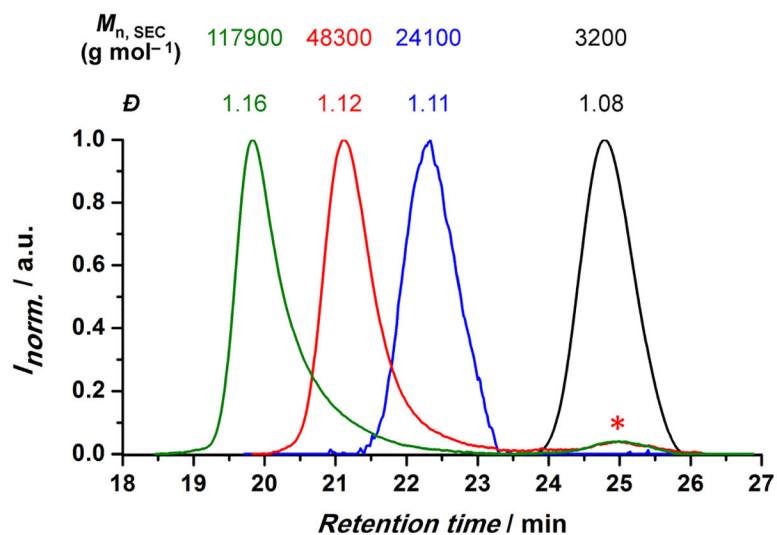


Figure 1. SEC traces in DMAc of **MM1** and of the BBPs obtained after the graft-through ROMP of **MM1** with THF as solvent and $[MM1] = 0.05$ M, at $[MM1]/[G3]$ ratios of 10 (blue), 25 (red), and 50 (green). The asterisk (*) denotes trace amounts of unreacted MM.

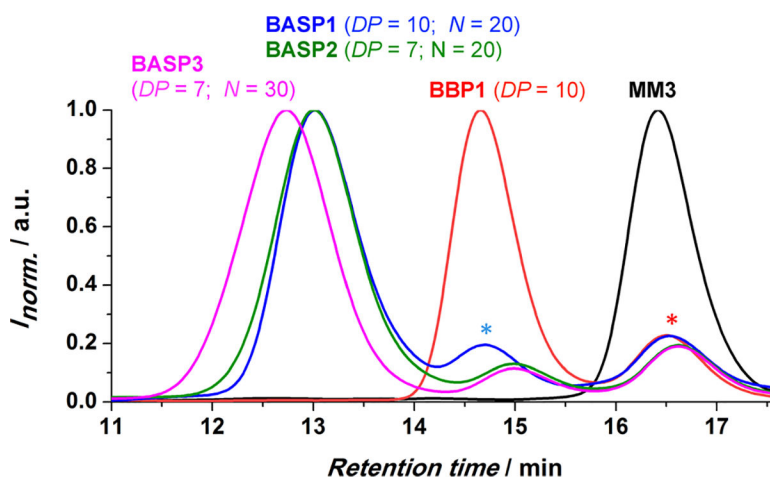


Figure 2. SEC traces in DMF (0.025 M LiBr) at 60 °C for **MM3**, chex-bottlebrush polymer **BBP1** (with $DP_{theo} = 10$), and BASP-ORCAs obtained by varying the **MM3**-to-**G3** ratio and the **AcetalXL**-to-**G3** ratio (N). Red “*” and blue “*” denote residual unreacted MM and BBP, respectively.

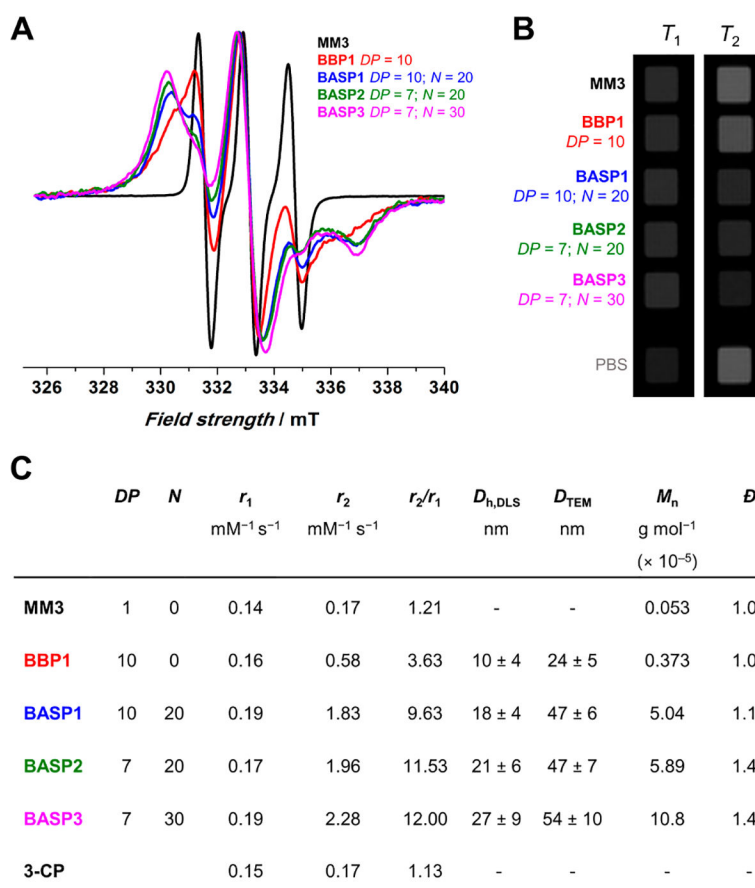
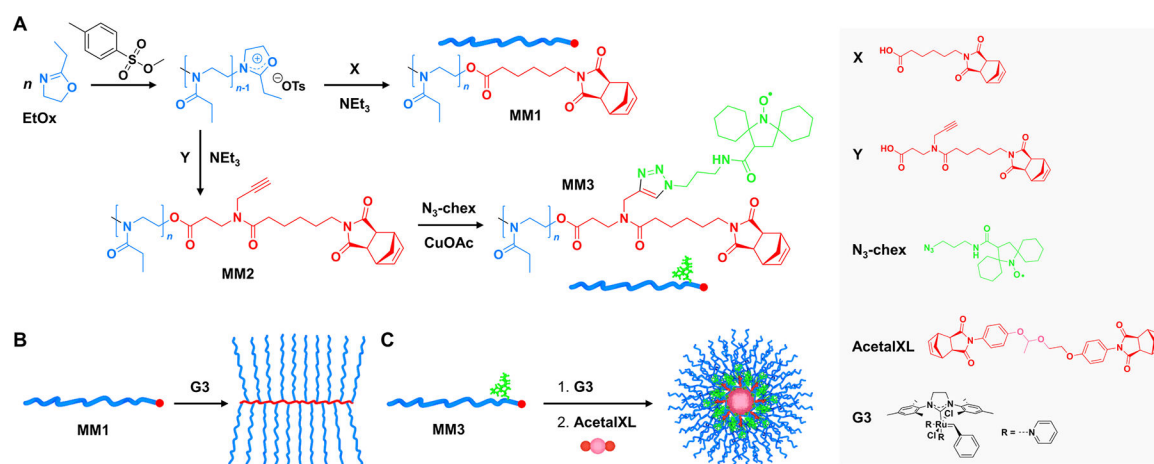


Figure 3. (A) EPR spectra of **MM3**, **BBP1** with $DP_{\text{theo}} = 10$, and BASP-ORCAs obtained by varying **MM3**-to-**G3** ratio (DP_{theo}) and cross-linker-to-**G3** ratio (N). (B) T_1 -weighted and T_2 -weighted phantom MR images for BASP-ORCAs dissolved in PBS. (C) Characterization data for the various chex-functionalized PEtOx architectures.

**Scheme 1.**

(A) Synthesis of PEtOx-Based Norbornene-Terminated MMs; (B) Graft-Through ROMP of Linear MMs (MM1) to Form Bottlebrush Polymers (BBPs); (C) Graft-Through ROMP of Branched MMs (MM3) Functionalized with chex to Provide Living BBPs, and Subsequent Addition of Cross-Linker AcetalXL to Yield PEtOx-Based BASP-ORCAs