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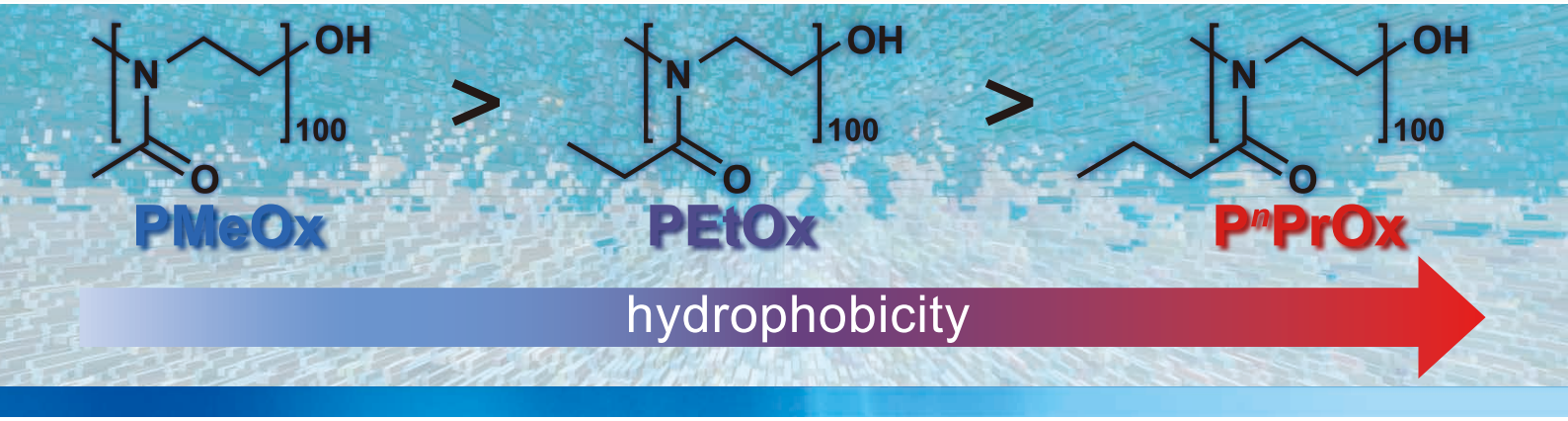

Contents

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Research Article

Poly(2-oxazoline)s: The Versatile Polymer Platform

Victor R. de la Rosa and Richard Hoogenboom

Abstract: Poly(2-oxazoline)s (commonly abbreviated as PAOx, POZ, POx or POXA) represent an extraordinary polymer platform with highly tunable properties and excellent biocompatibility, making them interesting in a broad variety of applications. The ability to vary the solubility and properties of PAOx via the side-chains is a highly interesting feature to be exploited for determining structure property relationships. The polymer hydrophilicity can be tuned from superhydrophilic via thermoresponsive to hydrophobic.
End-functional PAOx can be used as macroinitiators for block copolymer synthesis, or to confer the polymer properties (anti-fouling, thermoresponsive, *etc*.) to a substrate of interest. The high stability of PAOx against degradation is an important advantage of this polymer class with respect to surface functionalization applications.
Besides surface and nanoparticle functionalization, clickable and amino end-functional PAOx allow further modification and conjugation to a wide range of moieties, *e.g*., probes or biomolecules, using a variety of highly efficient coupling chemistries. The present article intends to provide an overview of the aforementioned application possibilities of PAOx focusing on examples involving readily available PAOx derivatives.

Keywords: poly(2-oxazoline)s, polymer platform, biocompatibility, terminal modification, conjugation

1. Introduction

Poly(2-oxazoline)s (commonly abbreviated as PAOx, POZ, POx or POXA) represent an extraordinary polymer platform with highly tunable properties, making them interesting as basis for future materials. First reported 50 years ago, PAOx reemerged in the new millennium due to improved synthetic methodologies and excellent biocompatibility, allowing their use in a broad variety of applications.[1]

The structural analogy of PAOx with natural polypeptides accounts for their excellent biocompatibility and stealth-behavior *i.e*. PAOx can be used to suppress interactions with proteins and cells which, in fact, is the key property that was at the basis of the wide-spread use of poly(ethylene glycol) (PEG). The properties of PAOx can be adjusted by simply varying the polymer side-chains. Glass transition temperature (T_g) can be varied from -10 to 80 °C using simple monomers[2] while solubility can be tuned from highly water soluble (poly(2-methyl-2-oxazoline) (PMeOx) and poly(2-ethyl-2-oxazoline) (PEtOx)) to thermoresponsive in water (poly(2-propyl-2-oxazoline) (PPrOx) derivatives) or water insoluble (PAOx with butyl of longer side chains) (**Figure 1**).

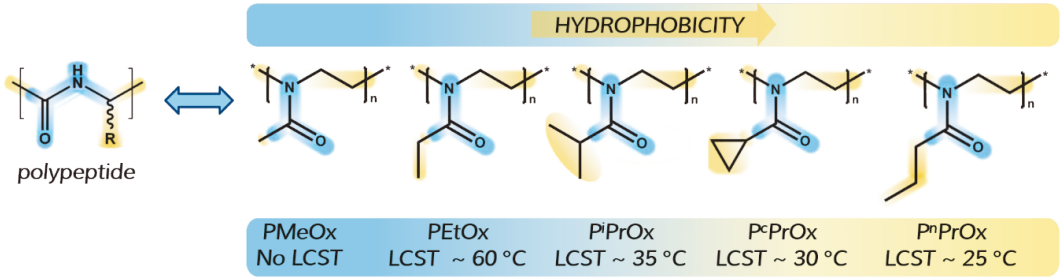

Figure 1. A series of PAOx derivatives displaying their structural analogy with polypeptides and their amphiphilic character. PAOx cover a broad lower critical solution temperature (LCST) range that can be finely tuned by copolymerization. PiPrOx and PnPrOx are structural isomers and potential alternatives to PNIPAM (LCST = 32 °C) (Adapted with permission from ref. 3).

PAOx can be prepared via living cationic ring-opening polymerization resulting in well-defined polymers with controlled end-groups that can be installed through initiation and termination (**Figure 2**). Under appropriate polymerization conditions, each initiator molecule initiates one polymer chain and all chains grow with a similar rate while chain transfer and chain termination do not occur, or are strongly suppressed. As a result, all polymer chains will have similar chain length and the ratio of monomer to initiator will determine the degree of polymerization (DP) at a certain monomer conversion.

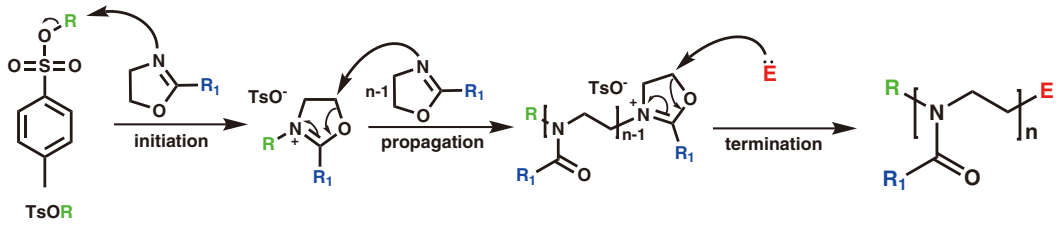

Figure 2. Overview of the cationic ring-opening polymerization (CROP) of 2-substituted-2-oxazolines, displaying the facile introduction of functionality at both the polymer chain-ends and side-chains.

2. Structure-property screening and formulation

The ability to vary the solubility and properties of PAOx via the side-chains is a highly interesting feature to be exploited for determining structure property relationships. Especially, the comparison of PMeOx, PEtOx and P^{n}PrOx allows screening over a wide range of aqueous solubility, from PMeOx that is more hydrophilic than PEG, *via* PEtOx that has similar aqueous solubility as PEG to P^{n}PrOx that is only soluble in water below 25 °C, above which it undergoes an LCST transition. PMeOx-OH, PEtOx-OH and P^{n}PrOx-OH with a DP of 100 and a hydroxyl group at the omega-terminus are available in the TCI catalog (**Figure 3**), and provide an excellent platform for deriving fundamental structure property relationships, either for direct formulation or for further modification and coupling reactions.

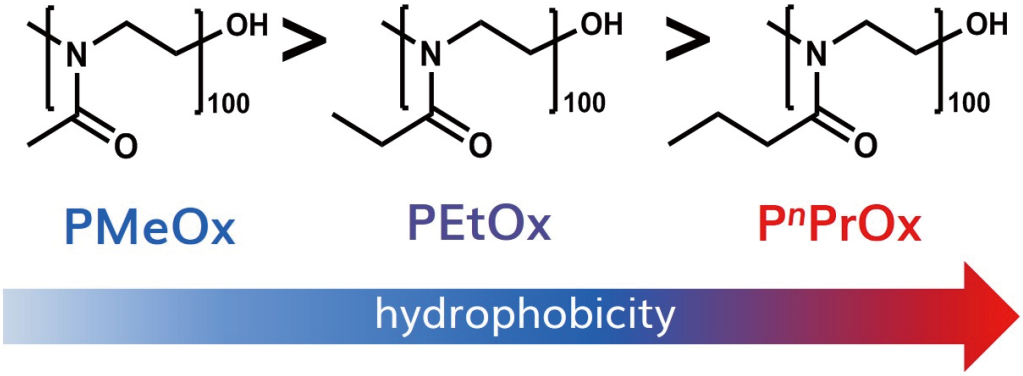

Figure 3. Hydroxy-terminated poly(2-oxazoline)s available in the TCI catalog.

The hydrogen bonding layer-by-layer assembly of PAOx with tannic acid was reported to be strongly dependent on the hydrophilicity of the PAOx, as PMeOx revealed purely enthalpic, hydrogen bonding driven assembly while P^{n}PrOx showed a purely entropy driven assembly based on the release of hydrating water molecules. PEtOx exhibited an intermediate behavior.[4] Furthermore, Khutoryanskiy *et al*. functionalized SiO_2 nanoparticles with PMeOx, PEtOx and P^{n}PrOx and investigated their permeation and diffusion through mucosal tissue.[5] The authors found a clear correlation between polymer hydrophilicity and permeability through the mucosal barrier, whereby the most hydrophilic PMeOx-grafted SiO_2 nanoparticles permeated significantly faster and deeper into the mucosa than their more hydrophobic PEtOx and P^{n}PrOx-grafted counterparts. A final example consists of the grafting of PMeOx, PEtOx or P^{n}PrOx on gold nanoparticles, revealing that their aggregation behavior can be strongly altered by changing the PAOx side chains.[6]

3. Poly(2-oxazoline) partial hydrolysis

Defined PAOx homopolymers can also be used for (partial) hydrolysis,[7] yielding poly(2-oxazoline)-co-polyethylenimine copolymers or linear polyethylenimine (L-PEI).[8] Partially hydrolyzed PAOx may serve as functional materials in which the secondary amine units in the main chains can be further modified to, *e.g.*, install methyl ester functionalities as additional reactive handles (see **Figure 4**).[9] Full hydrolysis followed by full reacylation has also been demonstrated to yield novel PAOx that are not easily attainable via CROP.[10] Furthermore, partially hydrolyzed P^{n}PrOx has been exploited as thermoresponsive gene delivery vector.[11]

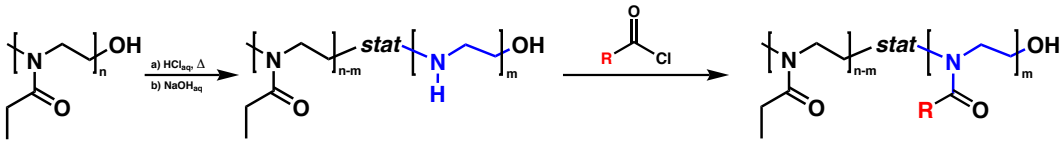

Figure 4. Partial hydrolysis of poly(2-ethyl-2-oxazoline) and subsequent functionalization.

4. End-group modification

Chain-end functionalized PAOx offer an excellent platform for derivatization at the polymer termini allowing, *e.g.*, facile grafting to (bio)molecules, surfaces and particles. In virtue of their high stability and biocompatibility, PAOx-functionalized surfaces[12] and nanoparticles[6] have potential uses in a variety of applications including implants, biosensors, imaging, or drug delivery.[3]

In analogy to PEG, end-functional PAOx have been successfully conjugated to biologicals for half-life extension, protection against degradation and immunogenicity prevention.[3,13] With over fifteen PEGylated pharmaceuticals in the market, PEG has proven extremely effective; however, its immunogenicity has become a significant issue, limiting further development of novel PEGylated therapeutics.[14] Thus, considering the biocompatibility and versatility of PAOx, PAOxylation or POZylation has been proposed as the new generation PEGylation.[14a,15]

The previously mentioned PEtOx and PMeOx-OH have been used for conjugation to polylysine (PLL), after conversion of the hydroxyl group to a carboxyl group via ring-opening of succinic anhydride. Subsequent coating of the PAOx-PLL induced efficient non-fouling properties to the substrate, whereby the PMeOx-g-PLL resulted in more efficient suppression of protein and cell adhesion compared to PEG-PLL and PEtOx-PLL (**Figure 5**).[16]

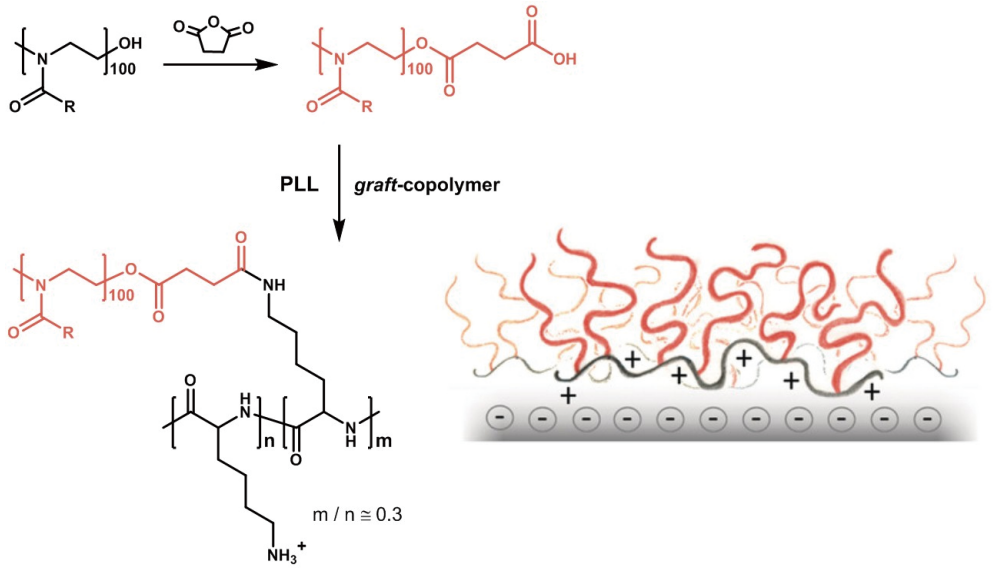

Figure 5. Surface functionalization with brush-forming PLL graft copolymers with different side-chain compositions (Adapted with permission from ref. 16a).

PEtOx-OH has also been demonstrated as efficient initiator for the controlled ring-opening of cyclic esters, directly yielding amphiphilic block copolymers.[17] Such block copolymers may be utilized for the encapsulation of drugs and their slow release based on hydrolysis of the polyester block.

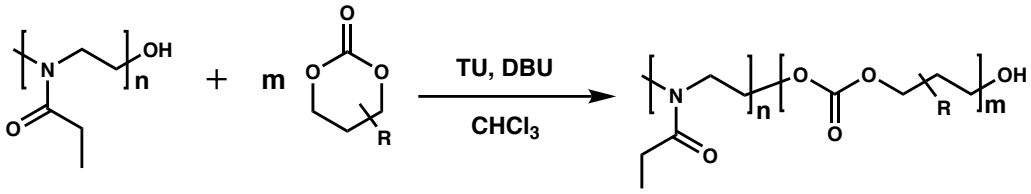

Figure 6. Schematic representation of the synthetic method for the preparation of block copolymers composed of 2-oxazolines and (functional) 6-membered cyclic carbonates.[17]

Besides the hydroxyl end-groups, azides and amino end-groups can be installed in PAOx through termination and post-polymerization functionalization, further expanding the conjugation possibilities.[18] Clickable PAOx-N_3 polymers enable efficient further modification via copper(I) catalyzed azide-alkyne cycloadditions with alkyne functionalized compounds, substrates or materials, as well as through strain-promoted azide-alkyne cycloadditions with strained alkynes.[19]

PMeOx and PEtOx with amine (-NH_2) end-functionalities allow the conjugation of the polymer to a wide range of moieties and substrates. PAOx-NH_2 can be easily reacted through a variety of chemistries such as activated esters, or iso(thio)cyanates. For example, substrates decorated with epoxides have been rendered protein repellent or antifouling by reaction with PEtOx-NH_2.[20] The distinctly high chemical stability of PAOx makes them especially interesting for surface functionalization.[21]

Figure 7 showcases some of the chemistries that enable the formation of stable poly(2-oxazoline) conjugates based on these functional hydrophilic polymers, which are currently available in the TCI catalog.

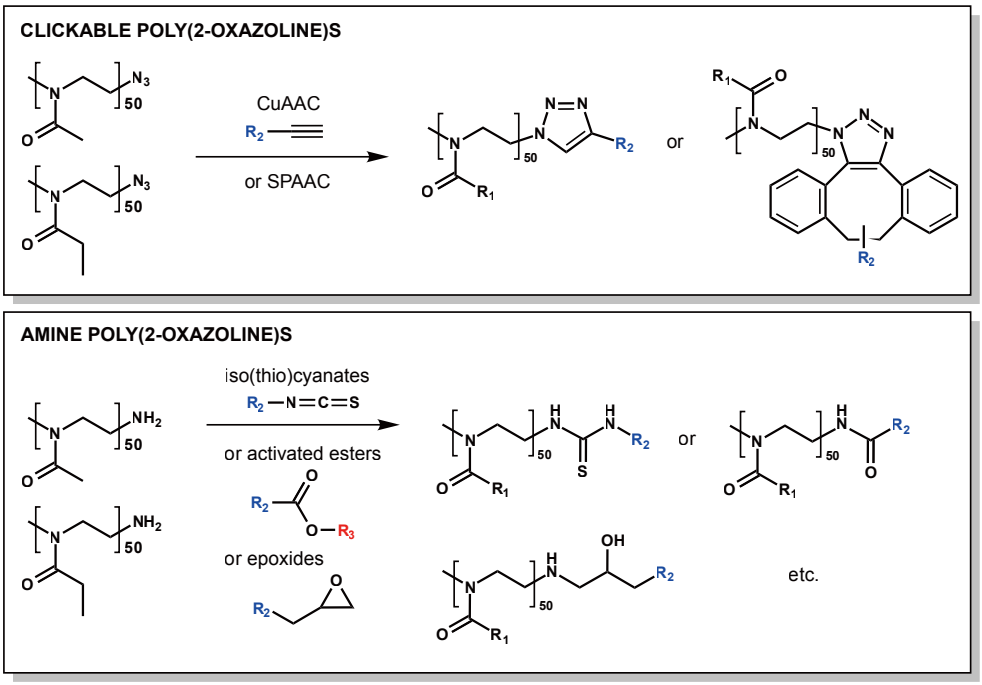

Figure 7. Conjugation reactions involving clickable and amine-functional poly(2-oxazoline)s. Amine-terminated poly(2-oxazoline)s can be used in combination with multiple other functional groups such as anhydrides, carbonates, aldehydes, etc.

5. Conclusions

The biocompatibility, tunable properties and high functionalization possibilities of PAOx make them a very attractive polymer platform for a broad spectrum of applications, ranging from biomedicine to smart materials and from personal care, via cosmetics to pharmaceuticals. The availability of PMeOx-OH, PEtOx-OH and P^nPrOx-OH with DP100 at TCI allows fast and efficient screening of the effect of polymer solubility on their formulation behavior and effectiveness for various applications. Moreover, they may serve as starting materials for the controlled (partial) hydrolysis towards functional PAOx. The chain-end-functionalized PAOx that are available with hydroxyl, azide and amino end-groups allow further modification and conjugation to a wide range of moieties, *e.g.*, biomolecules such as proteins and surfaces or (nano)particles.

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Author Information

Victor R. de la Rosa

Victor R. de la Rosa studied Chemistry at the University of Valladolid (UVa; Spain) and Ghent University (UGent; Belgium), where he spent a year within the Erasmus programme. Upon graduating in 2010, he returned to Ghent to conduct a PhD on poly(2-oxazoline)s and supramolecular chemistry under the supervision of Prof. Richard Hoogenboom.
In 2015, he was awarded an IWT post-doctoral grant (now VLAIO) to create a spin-off company based on the poly(2-oxazoline) platform. He developed and patented scalable processes for the production of high-quality poly(2-oxazoline)s, with a special focus on biomedical applications. He is co-inventor in several patents and has co-authored more than 20 scientific publications, mostly in the poly(2-oxazoline)s field.
Early 2018, Victor co-founded the spin-off company Avroxa bvba, dedicated to the design and production of poly(2-oxazoline)s under the Ultroxa brand name. Victor currently leads a team dedicated to poly(2-oxazoline) applied research and production, being responsible for the operations and R&D activities of Avroxa.

Richard Hoogenboom

Richard Hoogenboom studied chemical engineering at the Eindhoven University of Technology (TU/e; Netherlands). In 2005, he obtained his PhD under the supervision of Ulrich S. Schubert (TU/e) and continued working as project leader for the Dutch Polymer Institute; partly combined with a part-time position as Senior Product Developer at Dolphys Medical.
After postdoctoral training with Martin Möller at the RWTH Aachen (Humboldt fellowship; 2008) and Roeland J. M. Nolte at the Radboud University Nijmegen (NWO veni-grant; 2009), he was appointed as associate professor at Ghent University in 2010 and promoted to full professor in 2014.
His research interests include poly(2-oxazoline)s, stimuli-responsive polymers, and supramolecular materials, fields in which he is (co)inventor in more than 10 patent families and has co-authored over 300 scientific publications. He is currently associate editor for European Polymer Journal and Australian Journal of Chemistry.

Related Products

ULTROXA® Poly(2-methyl-2-oxazoline) (n=approx. 100)		200mg	P2506
ULTROXA® Poly(2-methyl-2-oxazoline) Amine Terminated (n=approx. 50)	100mg	500mg	U0135
ULTROXA® Poly(2-methyl-2-oxazoline) Azide Terminated (n=approx. 50)	100mg	500mg	U0134
ULTROXA® Poly(2-ethyl-2-oxazoline) (n=approx. 100)		500mg	P2507
ULTROXA® Poly(2-ethyl-2-oxazoline) Amine Terminated (n=approx. 50)	100mg	500mg	U0133
ULTROXA® Poly(2-ethyl-2-oxazoline) Azide Terminated (n=approx. 50)	100mg	500mg	U0132
ULTROXA® Poly(2-propyl-2-oxazoline) (n=approx. 100)		200mg	P2508

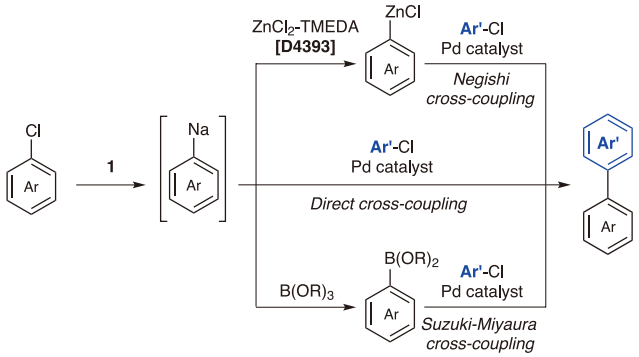
New Product Information

Sodium Dispersion Applicable to Organic Synthesis

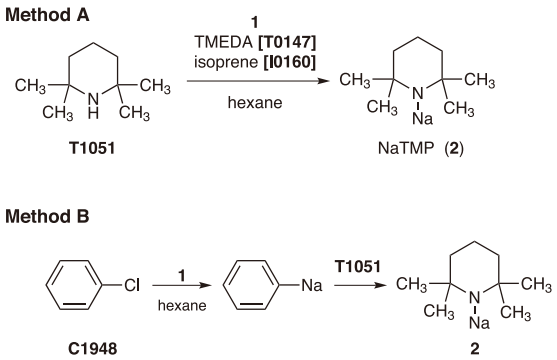
SD Super Fine™ (Sodium 25wt% dispersion in mineral oil) (1)

Product Number: **D5792**
5g 25g 100g

Sodium dispersions including SD Super Fine™ (**1**) have been used for the dechlorination of polychlorobiphenyls (PCBs) within industry. In recent years, many its application to organic synthesis such as Bouveault−Blanc reductions[1] and the reduction of tertiary amides[2] have been reported. For instance, Takai *et al*. reported a simple preparation of organosodium compounds from organic chlorides and **1** for cross-coupling reactions.[3] Organosodium compounds transmetallate with boron and zinc reagents to form organozinc and organoboron intermediates respectively. These intermediates can be readily applied to Negishi and Suzuki-Miyaura cross-coupling in the one-pot manner. In addition, the direct cross-coupling of arylsodiums and arylhalides can be achieved (Scheme 1). Takai *et al*. also developed lithium-free preparations of NaTMP (**2**) using **1** via method A and method B (Scheme 2).[4] **2** has proven to be effective for Wittig reactions, double-bond isomerizations, and functionalization of heteroarenes. In addition, Mori *et al*. have reported the preparation of anhydrous solvents using **1** as a dehydrating agent.[5] Owing to its large surface area, less reagent and time is required for dehydration, as well as a simplified quenching compared to large sodium lumps.



Scheme 1 Preparation of organosodium compounds using **1** and its application to cross-coupling reactions



Scheme 2 Preparation of NaTMP using **1**

*This product was commercialized with the cooperation and help from Kobelco Eco-Solutions Co., Ltd.
*Our items are distributed in accordance with local chemical regulations. Please note that some items are unavailable in some areas.

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Related Products

$ZnCl_2$-TMEDA			25g	D4393
2,2,6,6-Tetramethylpiperidine		25mL	250mL	T1051
N,*N*,*N*',*N*'-Tetramethylethylenediamine (TMEDA)	25mL	100mL	500mL	T0147
Isoprene (stabilized with TBC)		25mL	500mL	I0160
Chlorobenzene			500g	C1948

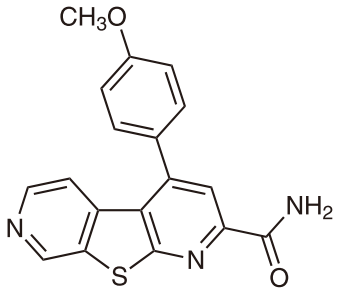
An Osteogenic Small Compound (TH)

TH (1)

Product Number: **M3085**
10mg 50mg

The helioxanthin analogue (TH) (**1**) is a first osteogenic small compound that was reported by Ohba *et al*.[1] In their reports, **1** not only stimulates osteoblast differentiation of osteoblast precursors, but also enhances bone regeneration in rodent bone defect models.[2,3] The osteogenic effects are also observed in mouse and human pluripotent stem cells[4,5] as well as human dental pulp stem cells.[6] **1** is one of the most promising compound for inducing bone regeneration.

This product is for research purpose only.



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Tetroses Rarely Existing in Nature

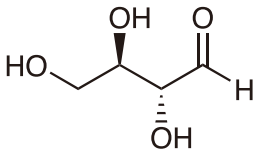
D-Erythrose (*ca*. 70% in Water) (1)

Product Number: **E0022**
200mg 1g

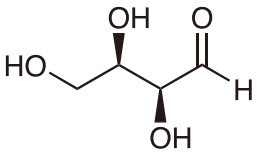
D-Threose (contains 35% Water at maximum) (2)

Product Number: **T3649**
200mg 1g

D-Erythrose (**1**) and D-threose (**2**) are rare sugars, monosaccharides (with 4 carbon atoms) found only in small amounts in nature. In plants and microorganisms, **1** is converted to D-erythrose-4-phosphate (4EP) by phosphorylation and then used in heptose phosphate pathway or shikimate biosynthesis pathway.[1] Moreover, **1** has proved to an inhibitor of tumor cell growth.[2] It has been reported that **2** suppresses mannitol dehydrogenase.[3]



1



2

References

1) H. H. Hiatt, B. L. Horecker, *J. Bacteriol*. **1956**, *71*, 649.
2) L.-L. Liu, T. Yi, X. Zhao, *Oncol. Lett*. **2015**, *9*, 769.
3) J. M. H. Stoop, W. S. Chilton, D. M. Pharr, *Phytochemistry* **1996**, *43*, 1145.

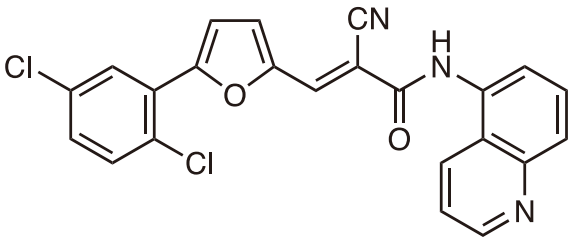
Related Product

meso-Erythritol	25g	100g	500g	E0021

SIRT2 Inhibitor

AGK-2 (1)

Product Number: **A3193**
5mg 25mg 100mg



1

Sirtuin 2 (SIRT2) is a histone deacetylase (HDAC) and plays an important role in cell cycle progression. AGK-2 (**1**) inhibits mammalian SIRT2 with IC_{50} = 3.5 μM.[1)], at the same time, **1** has less activity (at up to 40 μM) against SIRT1 and SIRT3. **1** also rescues dopamine neurons from α-synuclein–mediated toxicity in a *Drosophila* model of Parkinson's disease.

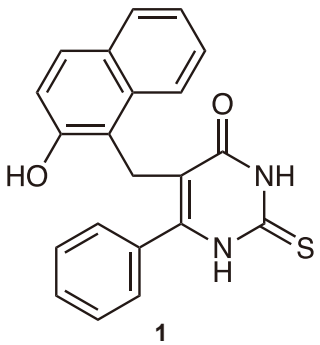
Reference

1) T. F. Outeiro, E. Kontopoulos, S. M. Altmann, I. Kufareva, K. E. Strathearn, A. M. Amore, C. B. Volk, M. M. Maxwell, J.-C. Rochet, P. J. McLean, A. B. Young, R. Abagyan, M. B. Feany, B. T. Hyman, A. G. Kazantsev, *Science* **2007**, *317*, 516.

SIRT1 and 2 inhibitor

Cambinol (1)

Product Number: **C3535**
5mg 25mg



1

Cambinol (**1**) is a cell-permeable inhibitor of sirtuin (SIRT) 1 and 2.[1)] The IC_{50} values to NAD-dependent deacetylation of acetyl-histone H4 peptide are 56 μM and 59 μM for SIRT1 and SIRT2, respectively. The inhibition manners are competitive for the substrate peptide and non-competitive for NAD. **1** also is inhibits sphingomyelinase 2 with Ki value of 7 μM.[2)] The inhibition manner is uncompetitive.

＊**1** is also known as NSC 112546.

References

1) B. Heltweg, T. Gatbonton, A. D. Schuler, J. Posakony, H. Li, S. Goehle, R. Kollipara, R. A. DePinho, Y. Gu, J. A. Simon, A. Bedalov, *Cancer Res.* **2006**, *66*, 4368.
2) M. Figuera-Losada, M. Stathis, J. M. Dorskind, A. G. Thomas, V. V. R. Bandaru, S.-W. Yoo, N. J. Westwood, G. W. Rogers, J. C. McArthur, N. J. Haughey, B. S. Slusher, C. Rojas, *PloS ONE* **2015**, *10*, e0124481.

CASA: New Chiral NMR Shift Reagents

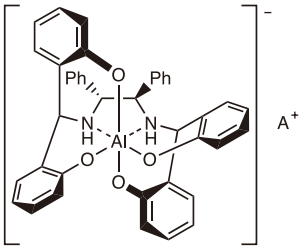
(*R*,*R*)-CASA-H (1) — Product Number: **C3671** **100mg**

(*S*,*S*)-CASA-H (2) — Product Number: **C3672** **100mg**

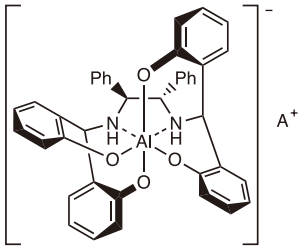
(*R*,*R*)-CASA-Na (3) — Product Number: **C3673** **100mg**

(*S*,*S*)-CASA-Na (4) — Product Number: **C3674** **100mg**

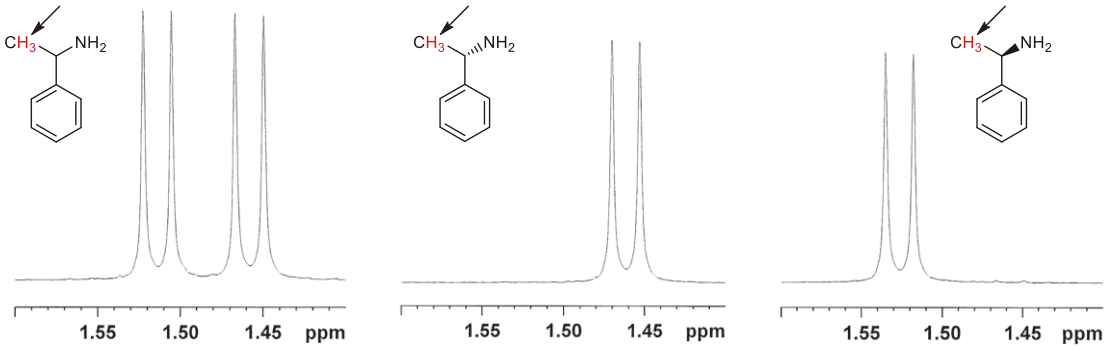
CASAs (**1**-**4**) are chiral hexa-dentate aluminum complexes usable as chiral shift reagents. When a mixture of a substrate and CASA are measured in NMR, the chemical shifts of the protons adjacent to oxygen and nitrogen functions are shifted, there by resolving the peaks of the two enantiomers present. Furthermore, CASAs are applicable to both polar and non-polar deuterated solvents.



A = H: **1**
A = Na: **3**



A = H: **2**
A = Na: **4**



NMR measurement of a mixture of **1** and 1-phenylethylamine
(Measured at TCI, 400 MHz, CD_3OD, racemic, *S* form, *R* form on right)

References

1) M.-S. Seo, H. Kim, *J. Am. Chem. Soc.* **2015**, *137*, 14190.
2) M.-S. Seo, S. Jang, H. Kim, *Chem. Commun.* **2018**, *54*, 6804.

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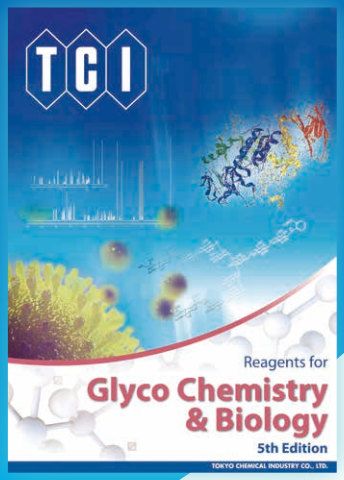

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