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Hypervalent Iodine(III) Compounds With (Pseudo)Halide And Tetrazole Ligands In The Synthesis Of Functional Polymers

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HYPERVALENT IODINE(III) COMPOUNDS WITH (PSEUDO)HALIDE AND TETRAZOLE

LIGANDS IN THE SYNTHESIS OF FUNCTIONAL POLYMERS

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LIGANDS IN THE SYNTHESIS OF FUNCTIONAL POLYMERS

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Advisor: Professor Nicolay V. Tsarevsky

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Hypervalent (HV) iodine(III) reagents have been widely applied to organic transformations owing to their ability to undergo various redox and ligand exchange reactions. HV iodine(III) compounds have also been employed in the synthesis of polymers, almost exclusively as polymerization initiators. This dissertation is focused on the utilization of HV iodine(III) reagents in the synthesis and functionalization of various macromolecules. The ligand exchange reaction at the HV iodine(III) center with nucleophiles, especially ones containing functional groups (e.g., bromine, azides, and isocyanate substituted carboxylates), provided a convenient source of functional radicals that were used in the polymerization of vinyl monomers and their *in-situ* postpolymerization. Furthermore, the synthesis of HV iodine(III) compounds containing various tetrazoles served as the reagents for the post polymerization of natural rubber to yield energetic materials. This method can be used to easily incorporate diverse functionalities in materials or to build up complex macromolecular architectures. The HV iodine(III) compounds were also used to demonstrate their versatile nature of serving as initiators and an efficient transfer agent. Several

synthetic approaches were developed utilizing HV iodine(III) chemistry to provide a versatile and

robust tool to synthesize advanced macromolecular materials.

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AcBIO   acitoxy benziodoxolones
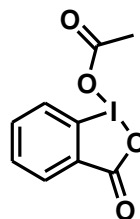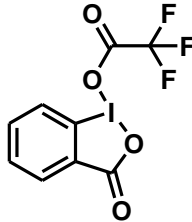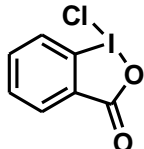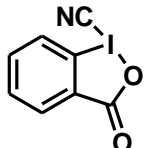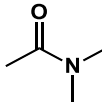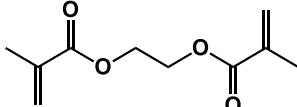
AcTZIB
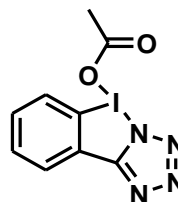
AIBN   azobisisobutyronitrile
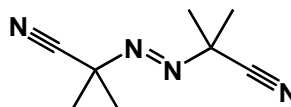
CF₃BIO	[bis(trifluoroacetoxy)iodo] benzene	
ClBIO	chloro benziodoxolone	
CNBIO	cyano benziodoxolones	
DMAc	dimethylacetamide	
DMSO	dimethyl sulfoxide	
DP	degree of polymerization	
EGDMA	ethylene glycol dimethacrylate	
FRP	free radical polymerization	

HBIO	hydroxyl benziodoxolone	
HTZIB		
HV	hypervalent	
IBA	2-iodobenzoic acid	
MeCN	acetonitrile	
MMA	methyl methacrylate	
$M_{n,app}$	apparent number-average molecular weight	
N_3BIO	azido benziodoxolone	
Pg_2O	propargyl ether	
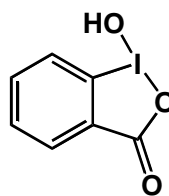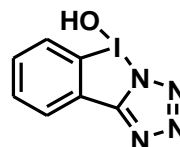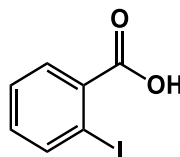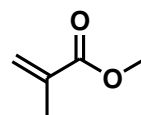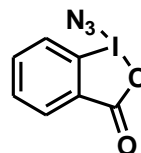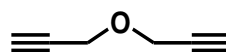
PhIO   iodosobenzene
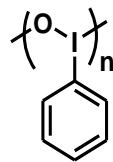
SCVP   self-condensing vinyl polymerization

SEC   size exclusion chromatography

T_g glass-transition temperature

THF   tetrahydrofuran

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1.1. History and Structure of HV Iodine(III) Compounds

Ever since their discovery in 1886 by Willgerodt,[1] HV iodine(III) compounds have continued to attract the attention of synthetic organic, theoretical, and materials chemists, and have found numerous applications, especially in organic synthesis, which are described in several monographs[2-6] and review papers.[7-14] The first of these compounds, dichloroiodobenzene (PhICl$_2$), was discovered by the German chemist Willgerodt in 1886 and was synthesized by the reaction of iodobenzene (PhI) and Cl$_2$. Soon after that, new HV iodine(III) compounds were described, including DAIB[15] and PhIO[16] in 1892, 2-iodoxybenzoic acid in 1893 and the first diaryl iodonium salts in 1894. The classification and nomenclature of HV iodine(III) compounds is based on the structural characteristics of these compounds. Because the iodine in HV iodine(III) compounds can exhibit the oxidation states of +3, +5 and +7, one common method based on electronic structures, referred to as the *Martin-Arduengo N-X-L designation*[17, 18] is widely used, where X is the central atom with variable valence, N is the number of valence shell electrons around the central atom, and L is the number of ligands. The structures and corresponding Martin-Arduengo designations of several HV iodine(III) species are shown in **Figure 1-1**.

| 10-I-3 | 12-I-4 | 10-I-4 | 12-I-5 | 14-I-6 | 14-I-7 |
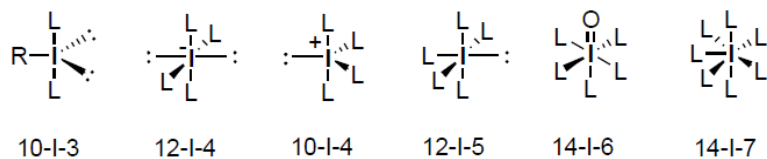
Figure 1-1. Structures and *Martin-Arduengo* nomenclatures of common HV iodine(III) species.

Owing to the unique reactivity of HV iodine(III) compounds of the type $ArIL_2$ (Ar = aryl; L = ligand, such as (pseudo)halide, carboxylate, etc.), namely their ability to participate in both radical (e.g., bond homolysis with the formation of iodoarenes ArI and radicals L[•])[19, 20] and ionic reactions (e.g., ligand exchange with nucleophiles Nu⁻, leading to compounds of the types ArILNu and eventually – $ArINu_2$), these compounds are of importance in the synthesis of functional macromolecules. Uses of $ArIL_2$ in polymer science and technology that have already been reported include i) initiators of radical polymerization,[21-27] ii) reagents for post-polymerization modifications (polymer-analogous reactions),[28-30] and iii) structural elements or building blocks of complex macromolecules.[31, 32] The iodine atoms in common HV iodine(III) compounds have either 10 or 12 valence electrons, and are known as either iodinanes and periodinanes, respectively. Iodanes are designated as λ^3- and λ^5-iodanes based on the lambda convention set forth by the 1983 IUPAC recommendations[33] that state that heteroatoms with nonstandard valence states (n) are named with λ^n notation (**Figure 1-2**). However, it should be noted that the older 1979 nomenclature rules of IUPAC and common names from older literature based on ligands attached to the iodine center are still widely used (**Table 1-1**).

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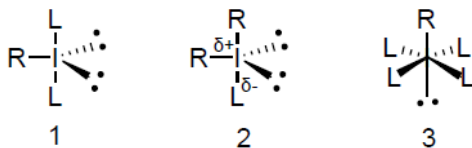
R = carbon ligand; L = heteroatom ligand

Figure 1-2. Molecular geometry of 1) λ^3-iodanes, 2) iodonium salts and 3) λ^5-iodanes.

Table 1-1. Nomenclature and abbreviations of common HV iodine(III) compounds.

Compounds	IUPAC names	Common names	Abbreviations
	(Dichloroiodo)benzene	Iodobenzene dichloride	IBD
		Iodosobenzene dichloride	
		Phenyliodo dichloride	
	(Diacetoxyiodo)benzene	Iodobenzene diacetate	DAIB
		Iodosobenzene diacetate	DIB
		Phenyliodo diacetate	IBD
	[bis(trifluoroacetoxy)iodo] benzene	Iodobenzene	BTI
		Bis(trifluoroacetate)	
	Iodosylbenzene	Iodosobenzene	IDB
	1-Hydroxy-1H-1λ^3-benzo[d][1,2]iodoxol-3-one	2-Iodosobenzoic acid 2-Iodosylbenzoic acid 1-Hydroxy-1,2-benziodoxol-2-(1H)-one	IBA
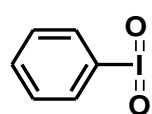
	Iodylbenzene	Iodoxybenzene	None
	1,1,1-Triacetoxy-1H-1λ^5-benzo[d][1,2]iodoxol-3-one	Dess-Martin Periodinate	DMP
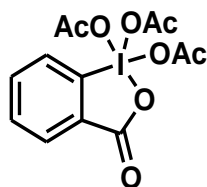
Polyvalent iodine compounds generally contain at least one carbon-based ligand, usually an aryl or perfluoroalkyl group, and single heteroatom ligands such as fluorine, chlorine, oxygen, or nitrogen. The iodine atom in the aryl-λ^3-iodanes (ArIL$_2$) has an overall T-shaped molecular geometry: two heteroatom ligands L located in the apical positions and an aryl ligand and lone pairs of electrons occupying the equatorial positions.[34] The two axial ligands L are attached to one of each lobe of the non- hybridized 5p orbital of iodine resulting a hypervalent three-center-four-electron bond (3c–4e bond)[35] which is composed of two electrons from iodine and one electron from each of the ligands L, as shown in **Figure 1-3**. The aryl group is bonded to the iodine center by a normal two-electron covalent bond. The length of the highly polarized 3c-4e bond is comparatively between that of a covalent bond and an ionic bond, according to experimental X-ray structural data, which accounts for the weak bonding of ligands in HV iodine(III) compounds.

For instance, the I-Cl bond lengths in PhICl$_2$ are 2.45 Å and the I-O bond lengths in PhI(OAc)$_2$ are 2.15-2.16 Å compared to, the respective sums of the covalent radii of I and Cl (2.41 Å), and I and O (1.99 Å).[36] The lability of 3c-4e bonds can also be explained by Molecular Orbital Theory. Three σ-molecular orbitals (bonding, nonbonding and antibonding) orbitals are generated via the orbital interactions between the p-orbital of iodine and two orbitals – one from each of the ligands. The four σ electrons occupy the two lower energy levels yielding weakly associated HV iodine (III) bonds. The two bonding electrons are delocalized over the two ligands, which results in the electrophilicity of the iodine center. Most of the electron density is located at the ends of the L-I-L triad, explaining why hypervalent iodanes could be stabilized by electronegative ligands and exhibit high electrophilic reactivity. The other types of λ^3- iodanes, iodonium salts, have similar pseudo-trigonal bipyramidal geometry with two carbon structure with an angle close to 90° and a closely associated anionic part of the molecule. Aryl λ^5-iodanes, ArIL$_4$, have a square pyramidal structure with an aryl group in the apical position and four heteroatom ligands in basal positions.
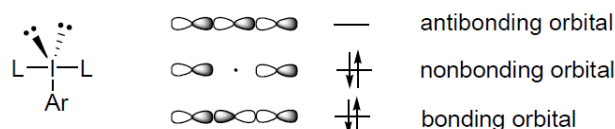
Figure 1-3. Molecular orbital of the 3c-4e bond in aryl-λ^3-iodanes (ArIL$_2$).

The λ^3-iodanes are overall the most abundant and relatively stable HV iodine(III) compounds. For this reason, their synthetic utility is most practical and will be the main focus of the research discussed in the remainder of this dissertation.

1.2. Ligand Exchange Reactions and Homolytic Fragmentation of HV iodine(III) Reagents

The reactivity of HV iodine(III) compounds is characterized by several factors, including the molecular structure of HV iodine(III), the lability of 3c-4e HV iodine(III) bonds, the electrophilicity of the iodine center, and the good leaving group ability of the iodoaryl group. The electrophilic iodine(III) center and the labile HV iodine(III) bonds allow susceptibility to efficient attack from nucleophiles, followed by the leaving of ligands. Ligand exchange reactions involving HV iodine(III) compounds have no well-established order of reactivity, which is mostly affected by the nature of substrates and solvents, but the general rule of "the better leaving group" similar to SN reactivity at carbon centers is always observed in the ligand transfer process. Two possible reaction patterns – associative and disassociative pathways – were proposed based on mechanisms similar to S_N1 and S_N2 reactions (**Scheme 1-1**).[37, 38] The dissociative pathway affords the unstable 8-I-2 cationic intermediates [ArIL]$^+$. The associate pathway involves the formation of a 12-I-4 species, followed by the isomerization and leaving of a ligand. A vast number of nucleophiles are able to participate in the ligand exchange reaction including F-, Cl-, RCOO-, CN-, N_3-, SCN-, OCN-, etc. affording a wide range of polyvalent derivatives. In general, the 3c-4e HV iodine(III) bonds are longer and less stable than regular covalent bonds. The homolytic dissociation can be triggered by heating, irradiation, or sonication.[38]
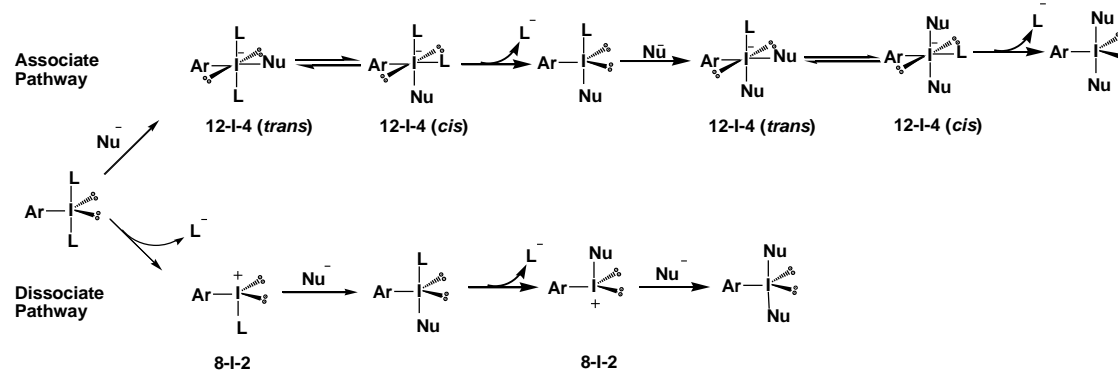
Scheme 1-1. Associate and dissociate pathways of ligand exchange reactions of HV iodoarenes, $ArIL_2$, in the presence of external nucleophiles, Nu^-.

1.3. Reactivity of HV Iodine(III) Reagents

Most organic HV iodine(III) species are thermodynamically unstable and some are known to be explosive, which requires most HV iodine(III) reagents to be freshly prepared and used. With that being said, there is still quite a selection of relatively stable organic HV iodine(III) compounds that are commercially available, including DAIB, BTI, [hydroxy(tosyloxy)iodo]benzene, IBA, 2-iodoxybenzoic acid, and Dess-Martin periodinane (DMP). In contrast, the inorganic polyvalent iodine derivatives show marked thermal stability and are commonly used as strong oxidants. For instance, iodine(V) oxide, I_2O_5, can efficiently convert carbon monoxide into carbon dioxide at room temperature and is used as a convenient reagent to detect carbon monoxide gas concentration.[39] Iodine pentafluoride is a fluorinating agent that can be handled in glass equipment and is widely used in many industrial situations.

Stable organic HV iodine(III) compounds, especially the λ^3-iodanes and λ^5-iodanes, are very useful in organic synthesis due to their versatile reactivities and benign environmental character. For instance, they are utilized as selective oxidants in organic transformations (**Scheme**

1-2). Organic HV iodine(III) reagents are employed to convert secondary alcohols into ketones and primary alcohols into carboxylic acids, and the use of the less oxidative λ^3- iodanes relative to λ^5-iodanes generally requires catalysts such as bromide salts or (2,2,6,6-tetramethyl-piperidin-1-yl)oxyl (TEMPO). Oxidations using HV iodine(III) reagents show great tolerance of functional groups, such as ethers, esters, sulfonates, azides, etc., and also give nearly quantitative yields that make them favorable and applicable for different synthetic purposes.

Scheme 1-2. Examples of using a) HV iodine(III) and; b) HV iodine(V) reagents as oxidants in the organic transformation of alcohols into carbonyl compounds.

HV iodine(III) reagents can also be used to introduce new chemical bonds, such as C-C, C-O, C-N, and C-X (X = halogen), during organic transformations via either nucleophilic substitution or radical addition mechanisms (**Scheme 1-2**). For instance, (difluoroiodo)arenes, particularly 4-(difluoroiodo)toluene (TolIF$_2$) due to its stability, solubility and facile preparation, were used as powerful fluorinating agents in many selective fluorination reactions. The fluorination of alkene derivatives using TolIF$_2$ proceeds through a nucleophilic substitution

pathway yielding the difluorination of various alkenes.[40, 41] Likewise, chlorination reactions using the (dichloroiodo)arenes, such as $PhICl_2$, proceed through either radical and ionic pathways depending on the chemical environment.[10, 42, 43] In general, the radical pathway is conducted in nonpolar solvents under photochemical conditions or in the presence of radical initiators, while the ionic approach is used in polar solvents. HV iodine(III) compounds can be diversified by ligand exchange reactions with various nucleophiles *in situ* providing convenient access to a number of functional groups.
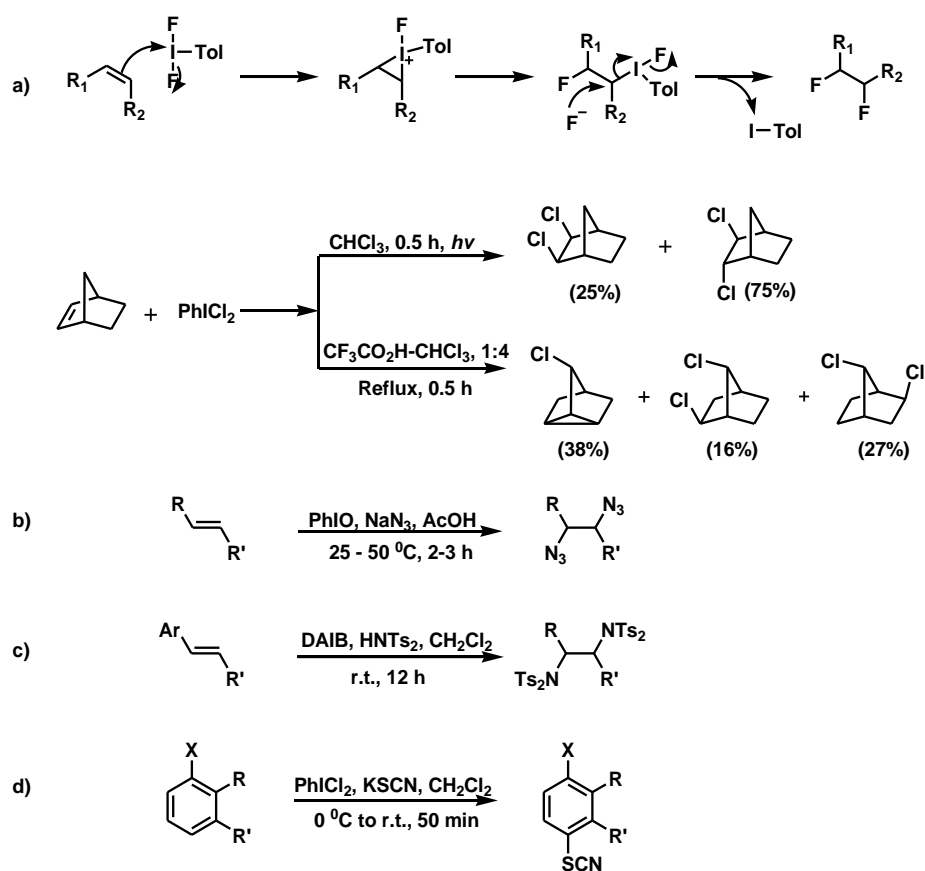
Scheme 1-3. Examples of organic HV iodine(III) reagents in the formation of new chemical bonds via a) halogenation,[40] b) azidation,[44] c) amination,[45] and d) thiocyanation.[46]

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In addition to the extensive applications as oxidants in organic synthesis, HV iodine(III) compounds can also participate in ligand (L) exchange and radical or ionic reactions. Recently, it was reported[47-49] that the ligands (L) in L-I-L bonds could be substituted by nucleophiles to afford new HV iodine(III) compounds, and the newly formed hypervalent I-Nu bonds could in turn dissociate homolytically and yield Nu$^{\bullet}$ radicals. For example, azide anions from NaN_3 efficiently substituted the acetoxy ligands in DAIB (**Scheme 1-4**). The new hypervalent bonds I-N_3 decomposed rapidly even at ambient temperature, generating $N_3^{\bullet}$ radicals as initiators to afford various azide-containing polymers.
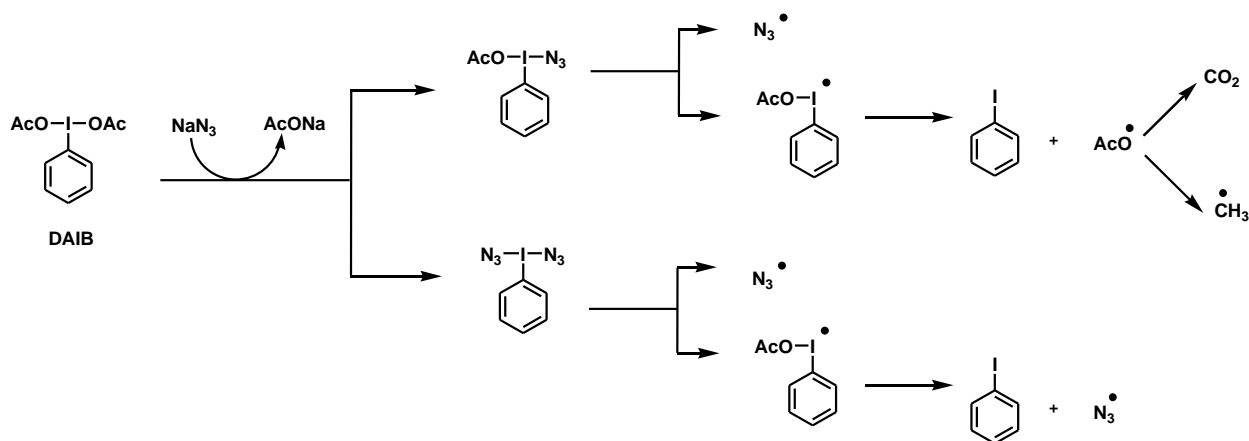
Scheme 1-4. Exchanging reaction of DAIB with sodium azide, generating azide radicals to initiate the polymerization of vinyl monomers.

Because of the relatively weak hypervalent bonds, HV iodine(III) compounds themselves can serve as initiators for radical and ionic polymerizations. For instance (**Scheme 1-5**), the hypervalent I-O bonds in $ArI(O_2CR)_2$ can be cleaved homolytically upon either heating or irradiation, and the generated radicals initiate free radical polymerization of vinyl monomers.[50-52] In addition, the photolysis of iodonium salts can generate cationic species, which are useful to initiate cationic polymerization of vinyl and heterocyclic monomers.[53, 54] Therefore, HV iodine(III)

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compounds may open new opportunities for synthetic chemistry, and particularly polymer chemistry in the fields of polymer modification, functional initiation, dynamic crosslinking, and also CRP systems. It should be mentioned that not every HV iodine(III) compound that generates radicals or cations can be used for CRP or dynamic materials.
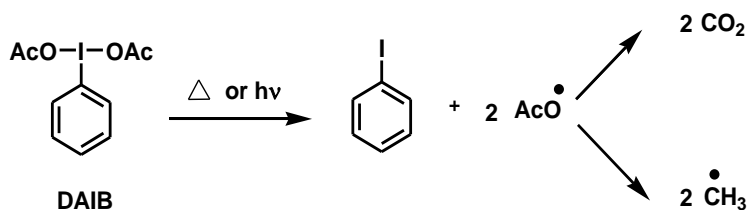
Scheme 1-5. HV iodine(III) compounds serving as initiators for radical and ionic polymerizations.

1.4. Benziodoxolone-derived reagents

Heterocyclic HV iodine(III) compounds, benziodoxolone (BIO) and its derivatives are of significant interest due to their simple preparation,[55-57] higher thermodynamic stability compared to acyclic HV iodine(III) compounds,[56] and various applications in organic synthesis including carbon- or hetero- atom transfer reactions have been described.[58] **Scheme 1-6**, shows the chemical structures of some popular BIO derivatives.
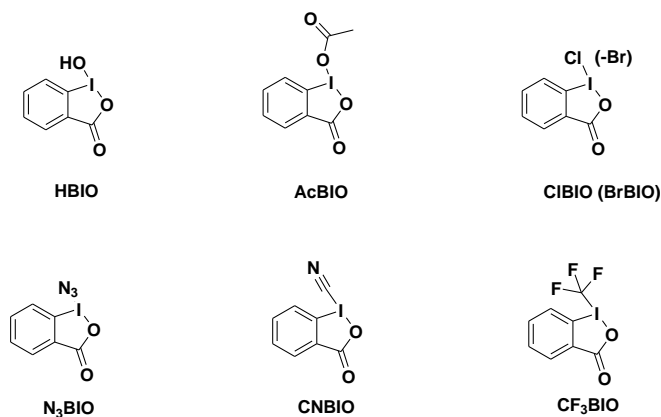
Scheme 1-6. Examples of BIO derivatives.

The greater stability can be explained by the bridging of an apical and an equatorial position by a five-membered ring and by conjugative overlap of the lone pairs of electrons on the iodine atom with the π-orbitals of the benzene ring,[59] which enables the isolation of otherwise unstable HV iodine(III) compounds with I-Br, I-N$_3$, I-CN, etc. For example, azido benziodoxolone (AzBIO) can be isolated as a thermally stable, microcrystalline solid, and can be stored at room temperature for several months without noticeable decomposition,[56] while in contrast, (diazidoiodo)benzene PhI(N$_3$)$_2$ decomposes rapidly even at -25 to 0 °C with the formation of iodobenzene and nitrogen (the latter formed by the coupling of azide radicals).[56] One of the most important and best investigated heterocyclic HV iodine(III) compounds is hydroxyl benziodoxolone (HBIO), which was discovered by Meyer,[15] and is the cyclic tautomeric form of 2-iodosylbenzoic acid. Based on X-ray crystal structure and theoretical studies, the cyclic form is the better representation.[60] The internal endocyclic I-O bond, which is 2.30 Å long and significantly longer than the computed covalent I-O bond length of 1.99 Å, indicates its hypervalent nature. In addition, the exocyclic I-O bond is 2.00 Å.[61]
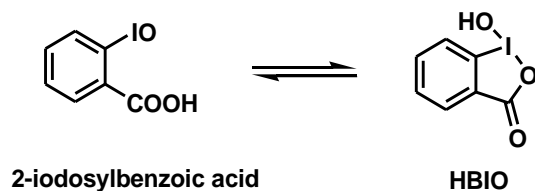
Scheme 1-7. Structures of 2-iodosylbenzoic acid and HBIO.

HBIO, as a precursor of various functional group-substituted BIOs, can be easily prepared by the oxidation of a commercially available and inexpensive compound 2-iodobenzoic acid (IBA).[60] For example, the reaction between IBA and $NaIO_4$ yields HBIO with a high purity, and the yield is typically more than 90%.[62] Starting from HBIO, a great variety of BIO-derived reagents can be synthesized, including AzBIO,[54] acetoxy benziodoxolone (ABIO),[63] chloro benziodoxolone (ClBIO),[64] trifluromethyl benziodoxolone (CF_3BIO),[63] cyano benziodoxolone (CNBIO),[65] etc. These and some future BIO-derived compounds are useful in functionalization reactions such as atom- or functional group transfer reactions.[66, 67]

1.5. References

1. C. Willgerodt, *Journal für Praktische Chemie*, 1886, **33**, 154-160.

2. C. Willgerodt, *Die Organischen Verbindungen mit Mehrwertigem Jod*, Ferdinand Enke, Stuttgart, 1914.

3. A. Varvoglis, *Organic Compounds of Polycoordinated Iodine*, Wiley-VCH, Angewandte Chemie 1992.

4. A. Varvoglis, *Hypervalent Iodine in Organic Synthesis*, Academic Press, San Diego, 1997.

5. T. Wirth, *Hypervalent Iodine Chemistry: Modern Developments in Organic Synthesis*, Springer, Berlin, 2003.

6. V. V. Zhdankin, *Hypervalent Iodine Chemistry: Preparation, Structure and Synthetic Applications of Polyvalent Iodine Compounds*, Wiley, Chichester, 2014.

7. R. B. Sandin, *Chemical Reviews*, 1943, **32**, 249-276.

8. D. F. Banks, *Chemical Reviews*, 1966, **66**, 243-266.

9. R. M. Moriarty and O. Prakash, *Account of Chemical Research*, 1986, **19**, 244-250.

10.   P. J. Stang and V. V. Zhdankin, *Chemical Reviews*, 1996, **96**, 1123-1178.

11.   V. V. Zhdankin and P. J. Stang, *Chemical Reviews*, 2002, **102**, 2523-2584.

12.   T. Wirth, *Angew. Chem. Int. Ed.*, 2005, **44**, 3656-3665.

13.   V. V. Zhdankin and P. J. Stang, *Chemical Reviews*, 2008, **108**, 5299-5358.

14.   A. Yoshimura and V. V. Zhdankin, *Chemical Reviews,* 2016, **116**, 3328-3435.

15.   V. Meyer and W. Wachter, *Chemische Berichte*, 1892, **25**, 2632-2635.

16.   C. Hartmann and V. Meyer, *Chemische Berichte*, 1893, **26**, 1727-1732.

17.   J. C. Martin, *Science*, 1983, **221**, 509.

18.   C. W. Perkins, J. C. Martin, A. J. Arduengo, W. Lau, A. Alegria and J. K. Kochi, *Journal of the American Chemical Society*, 1980, **102**, 7753-7759.

19.   T. Muraki, H. Togo and M. Yokoyama, *Reviews on Heteroatom Chemistry*, 1997, **17**, 213-243.

20.   X. Wang and A. Studer, *Acc. Chem. Res.*, 2017, **50**, 1712-1724.

21.   G. Georgiev, E. Kamenska, L. Christov, I. Sideridou-Karayannidou, G. Karayannidis and A. Varvoglis, *Eur. Polym. J.*, 1992, **28**, 207-211.

22. G. S. Georgiev, *Polym. Bull.*, 1999, **43**, 223-230.

23. G. S. Georgiev, E. B. Kamenska, N. V. Tsarevsky and L. K. Christov, *Polymer International*, 2001, **50**, 313-318.

24. G. Georgiev, E. Kamenska, N. Tsarevsky, L. Christov, N. Koseva and D. Proynov, *Ann. Univ. Sofia, Fac. Chim.*, 2002, **95**, 27-37.

25. H. Han and N. V. Tsarevsky, *Polym. Chem.*, 2012, **3**, 1910-1917.

26. A. D. Asandei, O. I. Adebolu, C. P. Simpson and J.-S. Kim, *Angew. Chem. Int. Ed.*, 2013, **52**, 10027-11030.

27. H. Han and N. V. Tsarevsky, *Chem. Sci.*, 2014, **5**, 4599-4609.

28. N. V. Tsarevsky, *J. Polym. Sci.: Part A: Polym. Chem.*, 2010, **48**, 966-974.

29. P. A. Ledin, N. Kolishetti and G.-J. Boons, *Macromolecules*, 2013, **46**, 7759-7768.

30. D. Liu and C. W. Bielawski, *Polym. Int.*, 2017, **66**, 70-76.

31. H. K. Livingston, J. W. Sullivan and J. I. Musher, *J. Polym. Sci.: Part C*, 1968, **22**, 195-202.

32. D. G. Ray III and G. F. Koser, *J. Org. Chem.*, 1992, **57**, 1607-1610.

33.   W. H. Powell, *Journal*, 1984, **56**, 769.

34.   P. J. Stang, *Angewandte Chemie*, 1993, **105**, 1277-1277.

35.   G. C. Pimentel, *The Journal of Chemical Physics*, 1951, **19**, 446-448.

36.   P. Kiprof, *ARKIVOC*, 2005, **2005**, 19-25.

37.   R. M. Moriarty and O. Prakash, *Accounts of Chemical Research*, 1986, **19**, 244-250.

38.   M. Ochiai, in *Hypervalent Iodine Chemistry: Modern Developments in Organic Synthesis*, ed. T. Wirth, Springer Berlin Heidelberg, Berlin, Heidelberg, 2003, pp. 5-68.

39.   N. N. Greenwood and A. Earnshaw, in *Chemistry of the Elements (Second Edition)* N. N. Greenwood and A. Earnshaw, Butterworth-Heinemann, Oxford, 1997, pp. 888-904.

40.   S. Hara, J. Nakahigashi, K. Ishi-i, M. Sawaguchi, H. Sakai, T. Fukuhara and N. Yoneda, *Synlett*, 1998, **1998**, 495-496.

41.   A. Bravo, F. Fontana, G. Fronza, F. Minisci and A. Serri, *Tetrahedron Letters*, 1995, **36**, 6945-6948.

42. A. Varvoglis, *Synthesis*, 1984, **1984**, 709-726.

43. E. B Merkushev, *Russian Chemical Reviews*, 1987, **56**, 1444-1479.

44. R. M. Moriarty and J. S. Khosrowshahi, *Tetrahedron Letters*, 1986, **27**, 2809-2812.

45. J. A. Souto, Y. González, A. Iglesias, D. Zian, A. Lishchynskyi and K. Muñiz, *Chemistry – An Asian Journal*, 2012, **7**, 1103-1111.

46. H. Kaur, R. Pundeer, R. S. Dhillon and S. P. Singh, *Synthetic Communications*, 2003, **33**, 4037-4042.

47. H. Han and N. V. Tsarevsky, *Polymer Chemistry*, 2012, **3**, 1910-1917.

48. H. Han and N. V. Tsarevsky, *Chemical Science*, 2014, **5**, 4599-4609.

49. R. Kumar, Y. Cao and N. V. Tsarevsky, *The Journal of Organic Chemistry*, 2017, **82**, 11806-11815.

50. G. Georgiev, E. Kamenska, L. Christov, I. Sideridou-Karayannidou, G. Karayannidis and A. Varvoglis, *European Polymer Journal*, 1992, **28**, 207-211.

51. G. S. Georgiev, E. B. Kamenska, N. V. Tsarevsky and L. K. Christov, *Polymer International*, 2001, **50**, 313-318.

52. A. D. Asandei, O. I. Adebolu, C. P. Simpson and J.-S. Kim, *Angewandte Chemie International Edition*, 2013, **52**, 10027-10030.

53. Crivello, J. V.; Lam, J. H. W. *Macromolecules* **1977**, *10*, 1307.

54. J. V. Crivello, *Journal of Polymer Science Part A: Polymer Chemistry*, 1999, **37**, 4241-4254.

55. V. V. Zhdankin, C. J. Kuehl, A. P. Krasutsky, M. S. Formaneck and J. T. Bolz, *Tetrahedron Letters*, 1994, **35**, 9677-9680.

56. V. V. Zhdankin, A. P. Krasutsky, C. J. Kuehl, A. J. Simonsen, J. K. Woodward, B. Mismash and J. T. Bolz, *Journal of the American Chemical Society*, 1996, **118**, 5192-5197.

57. L. Kraszkiewicz and L. Skulski, *ARKIVOC*, 2003, **2003**, 120-125.

58. J. P. Brand, D. F. González, S. Nicolai and J. Waser, *Chemical Communications*, 2011, **47**, 102-115.

59. V. Zhdankin and P. J Stang, *Chemical Reviews*, 2002, **102**, 2523-2584.

60. C. A. Panetta, S. M. Garlick, H. D. Durst, F. R. Longo and J. R. Ward, *The Journal of Organic Chemistry*, 1990, **55**, 5202-5205.

61.   M. Ochiai, *The Chemical Record*, 2007, **7**, 12-23.

62.   L. Kraszkiewicz and L. Skulski, *Optimized syntheses of iodylarenes from iodoarenes, with sodium periodate as the oxidant. Part II*, 2003.

63.   P. Eisenberger, S. Gischig and A. Togni, *Chemistry – A European Journal*, 2006, **12**, 2579-2586.

64.   X.-Q. Li and C. Zhang, *Synthesis*, 2009, **2009**, 1163-1169.

65.   V. V. Zhdankin, C. J. Kuehl, A. P. Krasutsky, J. T. Bolz, B. Mismash, J. K. Woodward and A. J. Simonsen, *Tetrahedron Letters*, 1995, **36**, 7975-7978.

66.   P. J. Stang and V. Zhdankin, *Chemical Reviews*, 1996, **96**, 1123-1178.

67.   T. Wirth and U. H. Hirt, *Synthesis*, 1999, **8**, 1271-1287.

CHAPTER 2.

IODOSYLBENZENE-PSEUDOHALIDE-BASED INITIATORS FOR RADICAL POLYMERIZATION

2.1. Introduction

2.1.1. Iodosylbenzene

Even though the iodosyl compounds have the chemical composition of ArIO, polymeric structure of the molecule causes their general expression of $(RIO)_n$. Thermal instability prevents the iodosylalkane from many practical uses, while the iodosylarenes are capable of being synthesized, isolated, and used under mild conditions. It should be kept in mind that drying of iodosylbenzene at an elevated temperature is to be avoided due to its lability, causing a violent explosion upon 110 °C *in vacuo* and a disproportionation reaction yielding PhI and explosive iodylbenzene. There is no structural evidence supporting the existence of a I=O double bond, instead, iodylbenzene exhibits a zigzag-shaped asymmetric bridge structure via the intra- and intermolecular bonding of primary I─O (2.04 Å) and secondary I▪▪▪O (2.37 Å) respectively **(Figure 2-1)**.[1, 2] This can lead to purification issues due to the resulting insolubility of iodosylbenzene in nonreactive organic solvents and inability to purify via recrystallization.
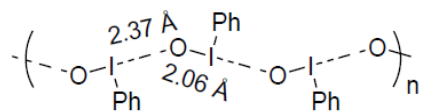
Figure 2-1. The structure of the polymeric state of PhIO.

One of the simplest synthetic approaches to PhIO is the oxidation of iodobenzene by dimethyldioxirane (DMDO) in acetone (**Scheme 2-2**),[1] which is also applicable for the synthesis of other organo-iodosyl compounds such as iodosylperfluoroalkanes R_fIO (R_f = perfluoroalkyl group). The proposed reaction mechanism involves the formation of the diradical intermediate by the PhI-induced homolysis of the peroxide bond. However, because of low product yield and over-oxidized impurity, iodosylarenes were generally prepared via the alternative route – hydrolysis of diacetoxy or (dichloroiodo)arenes (**Scheme 2-2**).
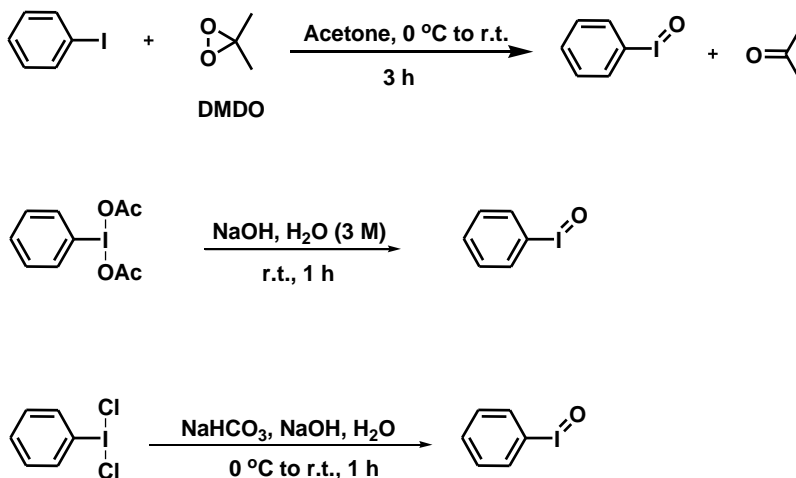
Scheme 2-1. Synthetic routes and conversions of PhIO.[3,4,5]

Iodosylbenzene can serve as a precursor for a variety of polyvalent iodine species, which makes it a great source of functional radicals applicable in small molecule synthesis and post-

polymerization modifications. For example, iodosylbenzene reacts with NaN_3 or $TMSN_3$ forming

the azido HV iodine(III) intermediates *in situ* which rapidly decompose and generate azide radicals

providing a convenient functionalization route to introducing azide groups.[6, 7]

2.1.2.   Reactivity of PhIO with psuedohalide sources

The ligand exchange reactions of the acyloxy groups in (diacyloxyiodo)arenes with

(pseudo)halide anions X^- or the reactions between iodosylarenes ArIO and trimethylsilyl

(pseudo)halides TMSX are convenient routes to (di(pseudo)haloiodo)arenes $ArIX_2$, which are

typically unstable and decompose *in situ* with the formation of (pseudo)halogen radicals, which

can react with numerous substrates, including compounds with unsaturated carbon-carbon bonds

or easy to abstract hydrogen atoms. In addition to chlorination radical reactions in the presence of

(dichloroiodo)arenes (typically not prepared by ligand exchange but by chlorination of the

corresponding iodoarene), numerous synthetically useful chemical transformations have been

reported involving, for example, azides and thiocyanates as the pseudohalogens. Very limited

number of ligand exchange reactions involving λ^3-iodanes of the type $ArIL_2$ and nucleophiles,

followed by homolytic cleavage (upon heating or irradiation with light) of the hypervalent bonds

of the newly formed iodanes have been reported that have application in the polymerization of

radically polymerizable monomers to yield directly functional polymers. For example, it was

shown[8] that the exchange of the acetoxy groups in DAIB with methacryloyloxy groups (i.e., in

reaction with methacrylic acid) is an easy way to prepare directly, without the need of isolation of

the reaction products, branched polymers, owing to the fact that both the produced

[(acetoxy)(methacryloyloxy)iodo]benzene or (dimethacryloyloxyiodo)benzene serve as both

initiators of polymerization and monomers (i.e., as inimers). The generation of azide radicals by a ligand exchange reaction between (diacetoxyiodo)benzene and NaN_3 and their use in the synthesis of linear and branched polymers with azide functionalities at the chain ends was also reported.[9]

The main goals of this work were i) to explore alternative hypervalent iodine(III)-based sources of azide and other (pseudo)halide radicals that could be employed to initiate polymerization and ii) to examine systematically the scope and limitations of (pseudo)halide radical-initiated polymerizations of various monomers.

2.2. Results and discussion

2.2.1. Polymerizations

The reactions of both TMSX and KX (X = (pseudo)halide) with either (diacetoxyiodo)benzene or PhIO are known to yield compounds of the type $PhIX_2$, which, depending on the nature of the group X, may be very unstable and decompose rapidly with the formation of (pseudo)halide radicals $X^\bullet$. These radicals, especially when present at high concentration, may couple to the corresponding (pseudo)halogen X_2, which may participate in further "side" reactions (for instance, when $X = N_3$, nitrogen is released, and when $X = SCN$, the initially produced dithiocyangoen $(SCN)_2$ undergoes oligomerization or polymerization with the formation of colored products[10]). However, in the presence of large amounts of unsaturated compounds (monomers), the radicals $X^\bullet$ may also initiate polymerization. The initiation step (with a rate coefficient k_i) in these cases, yields a monomeric radical (i.e., with a degree of polymerization DP = 1), which can react further with the monomer and propagate. Eventually, the

polymeric radicals, each containing an X group at the α-chain end, terminate by coupling (k_{tc}) or disproportionation (k_{td}), thus affording "dead" polymer chains with two or one X end-groups, respectively. In addition, the propagating radicals may terminate with the radicals X$^\bullet$ ($k_{t,X}$) or potentially abstract an X group from ArIX$_2$ (i.e., take part in transfer reactions (k_{tr})), both of which produce polymer chains with X groups at the ω-chain ends. Transfer of chlorine atoms from (dichloroiodo)arenes to various carbon-centered radicals is documented in the literature and some rate constants have been determined.[11] It could therefore be reasonably assumed that similar transfer reactions are likely to take place from the hypervalent iodine(III)-based initiator PhIX$_2$ generated via the reaction of iodosylbenzene with (pseudo)halides and the propagating polymeric radicals. All mentioned reactions and the corresponding rate coefficients are presented in **Scheme 2-2.**

Scheme 2-2. Polymerization of vinyl monomers initiated by the iodosylbenzene-pseudohalide system and formation of pseudohalide-capped polymers.[6]

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In addition to serving as radical precursors,[12, 13] hypervalent iodine(III) compounds can generate a number of cationic species, and in order to ensure that the polymerizations reported in this study were indeed radical (and not cationic), three of the monomers employed (MMA, VAc, and MA) were selected for their inability to undergo cationic polymerization. Several different PhIO-(pseudo)halide-based initiators were studied, all at 30 °C, including $TMSN_3$ and KN_3, TMSNCO and KOCN, and KBr (in all cases the molar ratio of PhIO and (pseudo)halide was 1:2), in two solvents of rather different polarity – DMAc and PhCl. The trimethylsilyl pseudohalides were soluble in the reaction mixtures and upon their addition to the mixtures of monomer, solvent, and PhIO, homogeneous solutions were formed within a short time period. The potassium (pseudo)halides have limited solubility in DMAc (especially in the presence of the weakly polar monomers), and even lower solubility in the rather nonpolar PhCl. All reaction mixtures, in which potassium salts were used as components of the initiating system, remained heterogeneous throughout the polymerization. All polymerization data is summarized in **Table 2-2**.

Table 2-1. Polymerization of Sty, MMA, VAc, and MA initiated by various PhIO-pseudohalide systems at 30 °C.

#	Monomer	Pseudohalide	$[M]_0/[in]_0$ [a]	Solvent	Conversion [%] (time [min])	$M_{n,app}$ [g mol^{-1}]; Đ [b]
1	Sty	$TMSN_3$	100	DMAc	12 (30)	8,730; 2.21
2			100	PhCl	10 (30)	2,230; 2.17
3		TMSNCO	100	DMAc	10 (600)	4,730; 2.01
4	MMA	$TMSN_3$	25	DMAc	53 (1,200)	2,120; 5.44
5			100	DMAc	20 (30)	6,500; 4.89
6			100	PhCl	21 (180)	5,125; 5.32
7			500	DMAc	12 (120)	4,520; 3.20
8		KN_3	100	DMAc	60 (1,740)	149,300; 2.32
9			500	DMAc	82 (3,000)	98,800; 3.59
10		TMSNCO	25	DMAc	77 (1,200)	24,440; 3.28

Entry	Monomer	Initiator	Ratio[a]	Solvent	Conv. % (time)	M_n; Đ[b]
11			100	DMAc	55 (900)	18,980; 2.70
12			100	PhCl	63 (1,440)	35,900; 2.21
13			500	DMAc	16 (600)	27,400; 2.11
14		KCNO	100	DMAc	78 (1,740)	87,500; 2.47
15			500	DMAc	86 (2,400)	122,800; 2.60
16		KBr	100	DMAc	70 (2,820)	31,630; 2.20
17	VAc	TMSN$_3$	100	DMAc	31 (30)	4,860; 1.90
18			100	PhCl	32 (30)	6,360; 1.76
19		TMSNCO	100	DMAc	30 (600)	5,940; 2.16
20	MA	TMSN$_3$	25	DMAc	81 (30)	3,840; 3.30
21			100	DMAc	72 (30)	17,050; 1.91
22			100	PhCl	91 (30)	30,760; 1.69
23			500	DMAc	61 (30)	3,300; 3.27
24		KN$_3$	100	DMAc	75 (180)	67,340; 2.04
25			500	DMAc	35 (120)	210,070; 2.11
26		TMSNCO	25	DMAc	88 (30)	15,770; 2.20
27			100	DMAc	92 (600)	33,860; 3.12
28			100	PhCl	94 (480)	142,000; 1.91
29			500	DMAc	36 (180)	93,600; 1.96
30		KCNO	100	DMAc	70 (180)	75,360; 2.06
31			500	DMAc	67 (300)	172,500; 2.32
32		KBr	100	DMAc	25 (300)	29,200; 2.22

[a] Molar/concentration ratio of monomer to initiator, where the initiator consisted of PhIO-pseudohalide (1:2 (n/n)). [b] Apparent number-average molecular weight and molecular weights distribution dispersities determined by SEC calibrated with linear polySty standards.

The polymerizations of MMA, in which PhIO-KX-based initiators were employed, were slower but reached higher monomer conversions and higher polymer molecular weights were attained compared to those, in which PhIO-TMSX-based initiators were used (**Table 2-2**). This is clearly seen by examining entries 5 and 8 (1 mol % of azide-based initiator vs. MMA), 7 and 9 (0.2 mol % of azide-based initiator vs. MMA), 11 and 14 (1 mol % of (iso)cyanate-based initiator vs. MMA), or 13 and 15 (0.2 mol % of (iso)cyanate-based initiator vs. MMA). Similar trends were observed in the polymerizations of the more rapidly polymerizing monomer, MA, especially with regards to reaction rates and molecular weights of the polymers, as can be ascertained by inspecting

entries 21 and 24 (1 mol % of azide-based initiator vs. MA), 23 and 25 (0.2 mol % of azide-based initiator vs. MA), 27 and 30 (1 mol % of (iso)cyanate-based initiator vs. MA), or 29 and 31 (0.2 mol % of (iso)cyanate-based initiator vs. MA). These results can be explained with the lower solubility of potassium pseudohalides compared to the corresponding TMSX compounds, which leads to slower but more "uniform" and continuous generation of the actual initiator, $PhIX_2$ (*vide infra* for further discussion). The nature of the solvent did not affect the polymerization rates and the monomer conversions (compare, for instance, entries 1 and 2 (Sty), 5 and 6 (MMA), 17 and 18 (VAc), or 21 and 22 (MA) for the $PhIO-TMSN_3$-based initiating systems, or 11 and 12 (MMA), or 27 and 28 (MA) for the PhIO-TMSNCO-based initiator), as expected for radical mechanism of polymerization. The solvent had a somewhat more pronounced impact on the molecular weights, particularly in the polymerizations of MA, where the reactions conducted in DMAc yielded polymers with lower molecular weights than those in PhCl (compare entries 21 and 22 or 27 and 28, in **Table 2-2**). This can be explained by the more pronounced transfer reactions with the former solvent. Although the transfer coefficients of polyacrylate radicals to DMAc and PhCl are not available in the literature, it is known[14] that for polystyrene radicals the transfer to DMAc (transfer coefficient $C_{DMAc} = k_{tr,DMAc}/k_p = 4.6 \times 10^{-4}$ at 60 °C) is more efficient than transfer to PhCl ($C_{PhCl} = k_{tr,PhCl}/k_p = 0.133\text{-}1.5 \times 10^{-4}$ at 60 °C).

Detailed polymerization kinetics data of all four studied monomers using the $PhIO-TMSN_3$ initiating system in DMAc are presented in **Figure 2-2(a)**. With the notable exception of the most rapidly polymerizing monomer, MA, all polymerizations stopped at relatively low monomer conversions. The polymer molecular weights (**Figure 2-2(b)**), again, with the exception of that of polyMA ($M_{n,app} = 17,050$ g mol^{-1}) were relatively low (< 9,000 g mol^{-1}).
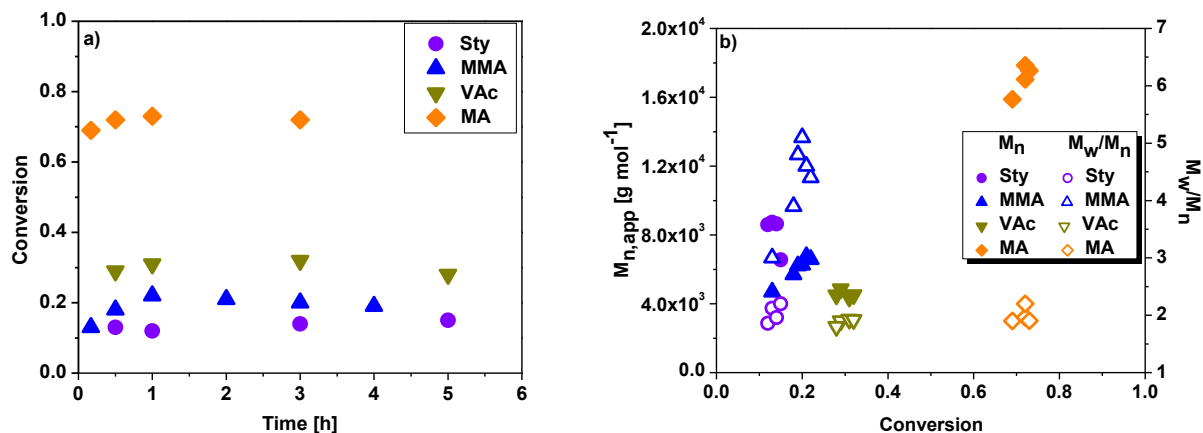
Figure 2-2. Kinetics (a) and evolution of molecular weights and molecular weight distribution dispersities (b) for the polymerization of Sty, MMA, VAc, and MA initiated by PhIO-TMSN$_3$ (1:2 (n/n); 1 mol % vs. monomer) at 30 °C in DMAc.

A comparison between five PhIO-pseudohalide initiating systems for the polymerization of MMA is presented in **Figure 2-3**. There was a very pronounced difference between the kinetics of the reaction in the presence of PhIO-TMSN$_3$ and PhIO-KN$_3$, the former being faster but stopping at lower conversion. With the (iso)cyanate-based initiators that difference was still observed, although it was less significant. The molecular weights of the polymers prepared with the PhIO-TMSX initiator were dramatically lower than those of polymers synthesized using the corresponding PhIO-KX systems, most likely due to efficient termination and/or transfer to the initiator (**Scheme 2-2**) when PhIX$_2$ was present at large concentrations (in the homogeneous mixtures). Interestingly, the PhIO-KBr-based initiator also afforded polymers (as opposed to vicinal dibromo-compounds) with reasonably high molecular weights using either MMA (**Table 2-2**, entry 16) or MA (entry 32) as the monomer. These reactions in all likelihood afforded polymers with one or two alkyl bromide end groups, but due to the fact that many other approaches

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are known for the synthesis of Br-capped macromolecules, for instance by atom transfer radical polymerization[15] or by transfer to CBr_4, these materials were not analyzed or studied further.
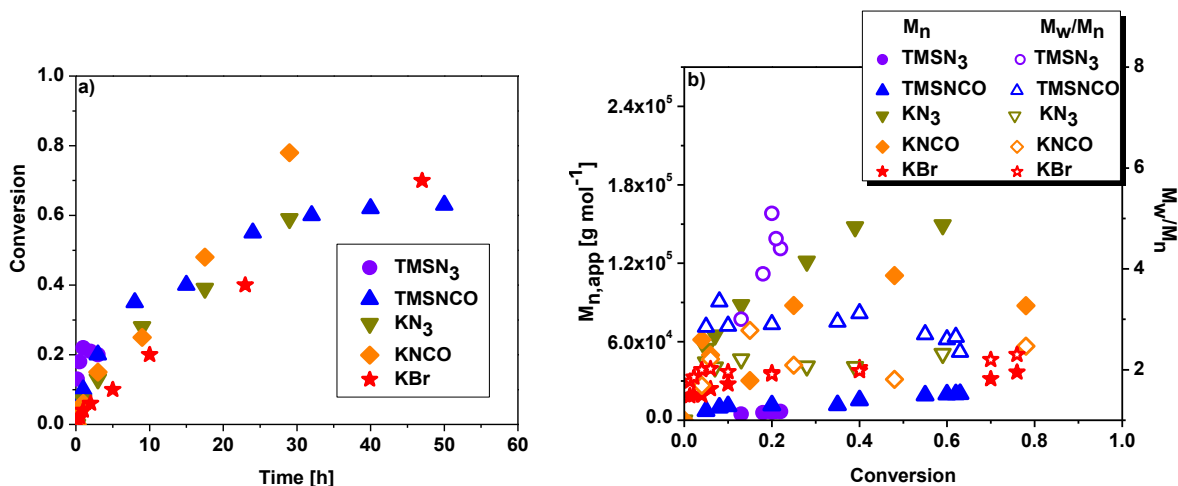
Figure 2-3. Kinetics (a) and evolution of molecular weights and molecular weight distribution dispersities (b) for the polymerization of MMA initiated by various PhIO-pseudohalide combinations (1:2 (n/n); 1 mol % vs. monomer) at 30 °C in DMAc.

In summary, in many of the studied polymerizations, particularly those of monomers with relatively low propagation rate coefficients, such as Sty and MMA, and those that were initiated by particularly unstable with respect to homolysis of the hypervalent I-X bonds (i.e., rapidly dissociating) initiators, such as the PhIO-TMSN$_3$ system, the limiting monomer conversions were relatively low. For example, when the ratio of monomer to PhIO-TMSN$_3$ initiator was 100, the conversions of Sty did not exceed 10-12 % before the polymerizations stopped (**Table 2-2**, entries 1 and 2) and these of MMA were of the order of 20 % (entries 5 and 6). Polymerization systems involving slowly polymerizing monomers and rapidly decomposing radical initiators are often named "dead-end polymerizations" and their kinetics was described in the late 1950s.[16, 17] The limiting conversion, i.e., the maximal conversion observed at "infinite" time ($conv_{max}$) depends

upon the ratio of the propagation and the square root of the termination rate coefficients (both monomer-dependent) as well as other reaction parameters, such as the rate coefficient of dissociation (k_d), the initial concentration of the initiator ($[in]_0$), and the initiation efficiency (f):

$$\text{conv}_{max} = 1 - \exp\left(-2\frac{k_p}{\sqrt{k_t}}\sqrt{\frac{f[in]_0}{k_d}}\right)$$

The maximal conversion for a series of monomers polymerized under identical conditions (temperature, solvent, as well as nature and concentration of radical initiator) will increase with the ratio $k_p/(k_t)^{1/2}$. The rate coefficients and the ratio in question (as well as the relative values of that ratio) for all studied monomers are presented in **Table 2-3**. Based on the data in that table, it is to be expected that the limiting conversion will increase in the order Sty < MMA < VAc < MA, which was indeed observed (**Table 2-2** and **Figure 2-2(a)**).

Table 2-2. Propagation (k_p) and termination (k_t) rate coefficients for the radical polymerization of the monomers studied in this work.

Monomer	k_p (30 °C) [M$^{-1}\cdot$s^{-1}] [a]	$k_t^{1,1}$ (25 °C) [M$^{-1}\cdot$s^{-1}] [b]	$k_p/(k_t)^{1/2}$	$k_p/(k_t)^{1/2}_{rel}$
Sty	107	$(1.1 - 1.2)\times10^8$	9.8×10^{-3}	1
MMA	369	$(4.2 - 6.6)\times10^7$	~0.05	5
VAc	3,985	$>5\times10^8$ (80 °C)	0.18	18
MA	14,800	1×10^9	0.46	47

[a] Calculated using the Arrhenius equation with pre-exponential factors and activation energies provided in ref. [18]
[b] Rate coefficient for termination between monomeric radicals.[19]

The molecular weights of the polymers are related to the kinetic chain length, which also depends on the ratio of the propagation and termination rate coefficients.[20] However, the data in

Table 2-3 is not suitable for prediction of molecular weights, because reactivity of the propagating radicals in transfer reaction should be taken into account. For example, the polymers derived from VAc (**Table 2-2**, entries 17-19) had low molecular weights, due to the very high reactivity of the corresponding polymeric radical in transfer reactions to initiator, monomer and/or polymer, and solvent.

2.2.2. Composition of the polymers

In order to prove the presence of pseudohalide chain end(s) (and possibly – pendant) groups in some of the polymers described in the previous section, it was essential to prepare low molecular weight materials. The PhIO-TMSN$_3$ initiating system was studied in detail because it yielded polymers with azide groups, which are easy to detect, even at low amount, by IR spectroscopy, due to the intense absorbance at ca. 2,100 cm^{-1} of that functionality, corresponding to the azide asymmetric stretching vibration.[21, 22] In addition, each azide group contains three nitrogen atoms, which makes it easy to detect by elemental analysis. Four polymers were synthesized derived from each of the studied monomers using the PhIO-TMSN$_3$-based initiator. For the preparation of azidated polymers derived from Sty and VAc (polySty(N$_3$)$_x$ and polyVAc(N$_3$)$_x$, respectively), 1 mol % of initiator relative to monomer was used in DMAc, for, as seen in **Table 2-2** (entries 1 and 17), low molecular weight polymers were readily obtained under these conditions. To prepare azide-containing polymers derived from MMA (polyMMA(N$_3$)$_x$) and especially MA (polyMA(N$_3$)$_x$) that were of as low as possible molecular weight and therefore suitable for spectral and elemental analyses, larger amount of initiator was used, namely 4 mol % vs. monomers (see entries 4 and 20 in **Table 2-2**). After thorough purification of the polymers by dialysis against

acetone (to ensure that all N-containing low molecular weight (non-oligomeric and non-polymeric) impurities, derived from PhIO-TMSN$_3$, or residual reaction solvent (DMAc) were removed), followed by drying, films were cast onto KBr plates, which were analyzed by IR spectroscopy. In addition, the elemental composition of the polymers was determined. The results are presented in **Figure 2-4**. All polymers contained nitrogen, which is consistent with the presence of azide at the chain end(s) and possibly the backbone. The amount of nitrogen was particularly large in the polySty(N$_3$)$_x$ sample, which suggested that in that case, the azide-capped polymer was possibly further azidated by the azide radicals that were still being generated in the system. Indeed, it has been shown[23] that the similar system (diacetoxyiodo)benzene-TMSN$_3$ is useful for the direct azidation of polySty, and, depending on the reaction conditions, as much as 1 out of 11 monomer repeat units per chain could be azidated.
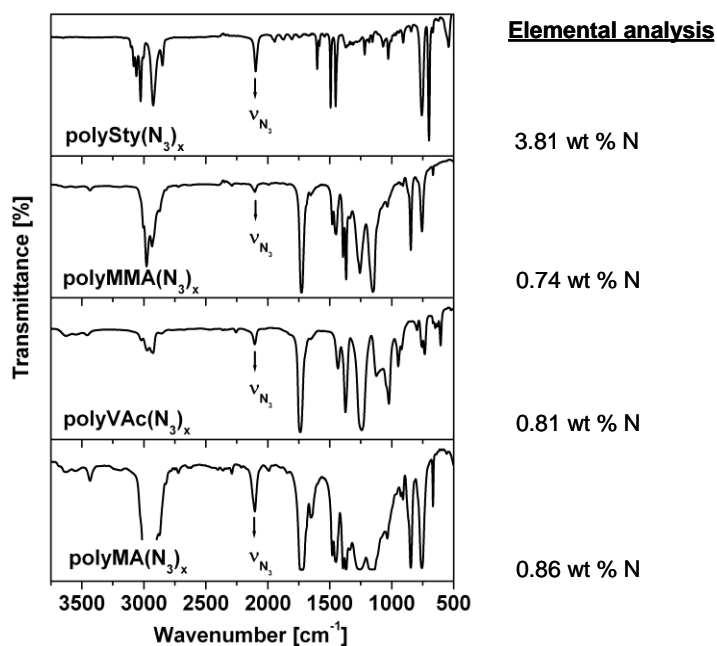
Figure 2-4. IR spectra (films cast on KBr plates) and nitrogen contents of polymers prepared using the PhIO-TMSN$_3$ initiating system (1 mol % (Sty and VAc) or 4 mol % (MMA and MA) vs. monomer) in DMAc.

Cyanates and isocyanates are also relatively easy to detect by IR spectroscopy. Both groups absorb IR light in the 2,280-2,240 cm^{-1} region.[21, 24] The spectra of polymers prepared from Sty and VAc using the PhIO-TMSNCO initiating system are shown in **Figure 2-5**. The (iso)cyanate absorbance is clearly seen, especially in the case of polySty(NCO)$_x$, suggesting that the mentioned hypervlent iodine initiator can be successfully employed for the direct synthesis of (iso)cyanate-functionalized polymers, which could find applications in the synthesis of polyureas or polyurethanes.
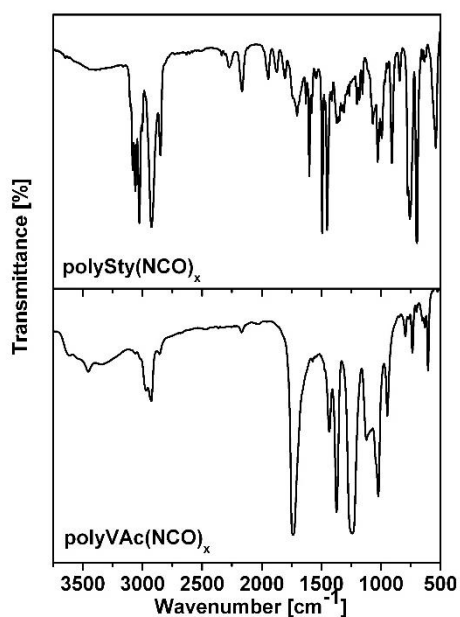
Figure 2-5. IR spectra (films cast on KBr plates) of polymers prepared using the PhIO-TMSNCO initiating system (1 mol % vs. monomer) in PhCl.

2.2.3. Modifications (coupling reactions) of (pseudo)halide-containing polymers

The presence of azide groups in the polymers prepared using the PhIO-TMSN$_3$ initiating system makes them suitable substrates for various types of modifications, due to the diverse reactions, in which azides can participate.[25-32] Of particular interest is the use of azide-containing polymers as building blocks of complex functional macromolecules, e.g., by azide-alkyne click chemistry.[33-40] The azide-containing polymers (**Table 2-4**, entries 1-4) derived from Sty, MMA, VAc, and MA were reacted with a dialkyne, Pg$_2$O (using an equimolar ratio of azide groups (determined by elemental analysis) and acetylene groups), in the presence of CuBr as the catalyst of the 1,3-cycloaddition. In all cases, the click coupling reactions led to the formation of polymers with higher molecular weight than the starting materials, indicating that the majority of macromolecules contained at least one azide functionality, as expected from the reaction mechanism represented in **Scheme 2-2**.

Table 2-3. Molecular Weights and Molecular Weight Distribution Dispersities of Pseudohalide-Containing Polymers Prepared by Using the PhIO-TMSN$_3$ or PhIO-TMSNCO Initiating Systems before and after Modification with Difunctional Coupling Agents[a]

#	Polymer	Elemental analysis (wt % N)	$M_{n,app}$ [g mol^{-1}]; Đ	Coupling reagent	$M_{n,app}$ [g mol^{-1}]; Đ (after coupling)
1	polySty(N$_3$)$_x$	1.12	4200; 2.04	Pg$_2$O (+CuBr), DMF, r.t.	13000; 4.87
2	polyMMA(N$_3$)$_x$	0.74	8800; 4.89	Pg$_2$O (+ CuBr), DMF, r.t.	13600; 3.60
3	polyVAc(N$_3$)$_x$	0.83	8100; 2.77	Pg$_2$O (+ CuBr), DMF, r.t.	19 900; 2.92
4	polyMA(N$_3$)$_x$	0.86	9200; 4.53	Pg$_2$O (+ CuBr, DMF, r.t.)	12 500; 3.97
5	polySty(NCO)$_x$	3.12	5800; 2.58	H$_2$N-(CH$_2$)$_3$-NH$_2$, THF, r.t.	14 800; 14.96
6	polyVAc(NCO)$_x$	2.26	4200; 2.10	H$_2$N-(CH$_2$)$_3$-NH$_2$, THF, r.t.	13 600; 13.21

[a]Samples were collected and analyzed after 15 h.

The SEC traces of two of the azide-containing polymers, polySty(N$_3$)x (entry 1 in **Table 2-4**), and polyVAc(N$_3$)x (entry 3 in **Table 2-4**). along with the evolution of these traces during the Cu(I)-catalyzed reaction of the polymers with Pg$_2$O in DMF over a 15-h period are shown in **Figure 2-6 (a)**. Upon click coupling, the entire molecular weight distribution shifted toward higher apparent molecular weights (shorter elution times or smaller elution volumes), although the "tailing" toward the low molecular weight region on the SEC traces of the coupling products suggested that there were some unreacted chains of the original polymer. In the case of click coupling of polySty(N$_3$)x, at longer reaction times (ca. 21 h), the reaction mixture became very viscous and it was difficult to withdraw samples from it; after dilution in the SEC solvent, THF, the solution could not be passed through a 0.2 μm PTFE syringe filter without applying high force, indicating that by that point, cross-linking reactions had commenced. This suggests that at least some of the chains contained more than two azide groups, as expected from the reported[7] reaction between polySty and azide radicals, which yields backbone- and pendant-group-azidated polymer. The SEC results serve as another proof (in addition to elemental analysis, IR, and NMR spectra) of the existence of azide groups in the polymers.

Cyanates[41] and isocyanates[42, 43] are also reactive functionalities, with numerous applications in organic syntheses and materials science. One of the most important (and large-volume) applications is the synthesis of polyurethanes and polyureas. The polymers synthesized by using the PhIO-TMSNCO initiating system contained (as seen in the IR spectra in **Figure 2-5**) (iso)cyanate groups and were therefore suitable candidates for reactions with diols or diamines. If more than two (iso)cyanate groups were present on average per chain, the reactions were expected to yield first highly branched and eventually network polymers. If the number of functionalities

per chain were smaller, than simple coupling (i.e., increase in the apparent molecular weight) would be observed. The results presented in **Table 2-4** (entries 5 and 6 for samples collected after 15-h stirring at r.t. in THF) clearly confirm that the (iso)cyanate groups were attached to the polymer chains. Samples were collected at 5 and 15 h, and the changes in the shapes of the molecular weight distributions, compared to the precursors, are shown in **Figure 2-7**. The very significant broadening of the molecular weight distributions was the result of some unreacted polymer (possibly due to the fact that some of the (iso)cyanate groups were hydrolyzed, as indicated by the IR spectra shown in **Figure 2-5**). However, although a fraction of the (iso)cyanate groups in the polymers were "lost", which altered the ratio between (iso)cyanate and amine groups (originally set to the ideal molar ratio for reaching high molecular weights of 1:1), branching and eventually gelation still occurred (in ca. 35 h) with the polySty(NCO)$_x$.
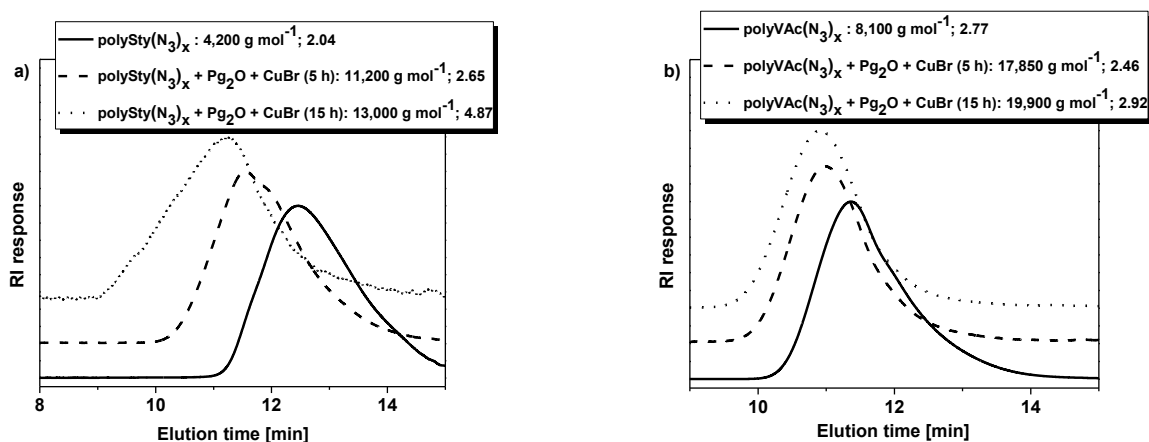
Figure 2-6. Evolution of SEC traces of polySty(N$_3$)$_x$ (a) and polyVAc(N$_3$)$_x$ (b) prepared by using the PhIO-TMSN$_3$ initiating system (1 mol % vs monomer in PhCl) during CuBr-catalyzed click coupling reactions with Pg$_2$O in DMF at r.t. The last two numbers in each of the rows in the legend indicate the apparent number-average molecular weight and the molecular weight distribution dispersity, respectively.
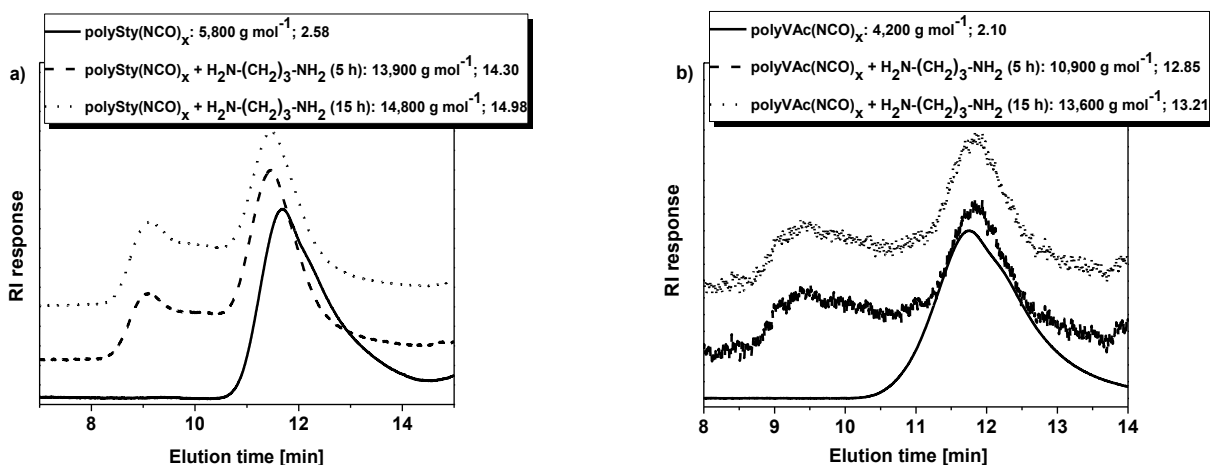
Figure 2-7. Evolution of SEC traces of polySty(NCO)$_x$ (a) and polyVAc(NCO)$_x$ (b) prepared by using the PhIO-TMSNCO initiating system (1 mol % vs monomer in PhCl) during coupling reactions with 1,3-propylenediamine in THF at r.t. The last two numbers in each of the rows in the legend indicate the apparent number-average molecular weight and the molecular weight distribution dispersity, respectively.

2.3.   Experimental

2.3.1.   Materials

Methyl methacrylate (MMA, 99%, Aldrich), methyl acrylate (MA, 99%, Aldrich), styrene (Sty, 99%, Acros), and vinyl acetate (VAc, 99%, Acros) were purified before the experiments by passing the neat monomer through a column filled with basic alumina, which absorbs the phenolic polymerization inhibitor present in commercial samples. Iodosylbenzene (PhIO) was synthesized using a procedure described in the literature,[44] which is based on the hydrolysis of (diacetoxyiodo)benzene (98%, Acros) with 3M aqueous NaOH (pellets, 97+%, Sigma-Aldrich, were employed to prepare the solution), followed by washing with chloroform (99% extra pure, Acros). Trimethylsilyl azide (TMSN$_3$, 94%, Alfa Aesar), trimethylsilyl isocyanate (TMSNCO, 85%, Sigma-Aldrich), trimethylsilyl bromide (TMSBr, 97%, Sigma-Aldrich), KN$_3$ (99.9%,

Sigma-Aldrich), KOCN (96%, Sigma-Aldrich), KBr (99%, Acros), propargyl ether (Pg$_2$O, 98%, Aldrich), CuBr (99.99%, Aldrich), 1,3-diaminopropane (99%, Acros), and the solvents, including anhydrous *N,N*-dimethylacetamide (DMAc, 99.5%, Acros), anhydrous ether (98%, EMD Millipore), petroleum ether (technical grade, EMD Millipore), *N,N*-dimethylformamide (DMF, 98%, EMD millipore), and tetrahydrofuran (THF, 99%, Fisher) were used as received. Chlorobenzene (PhCl, 99%, Acros) was dried over anhydrous sodium sulfate prior to use. The deuterated solvent, CDCl$_3$, (99.8% D, Cambridge Isotope Laboratories) contained a small amount of tetramethylsilane (TMS) as a chemical shift reference.

2.3.2. Analyses

Monomer conversion was determined by NMR spectroscopy using the Bruker Avance DRX (400 MHz) spectrometer. Samples were withdrawn periodically during polymerization using a nitrogen-purged syringe equipped with a Teflon-coated needle and diluted CDCl$_3$ to monitor monomer conversion. Molecular weights (number average (M_n) and weight average (M_w)) and molecular weight distribution dispersities ($Đ = M_w/M_n$) were determined by size exclusion chromatography (SEC) on a Tosoh EcoSEC system equipped with a series of 4 columns (TSK gel guard Super HZ-L, Super HZM-M, Super HZM-N, and Super HZ2000) and using THF as the eluent (30 °C) and a refractive index detector. The SEC was calibrated using a series of linear polySty standards. Prior to the chromatographic analyses, the samples were diluted with THF and filtered through Acrodisc 0.2 μm PTFE syringe filters. Elemental analyses were carried out at Midwest Microlab, IN. Infrared (IR) spectra were collected on a Thermo Scientific Nicolet iS10 FT-IR Spectrometer. The samples were prepared by dissolving 20 mg of polymer in 1 mL of

chloroform, followed by casting a film on a KBr plate by slow evaporation of the solvent (achieved by covering the salt plate with the polymer solution with a beaker).

2.3.3. Synthetic procedures

Synthesis of polymers using the PhIO-TMSX (X = N$_3$ or NCO) initiating system

In a 10-mL dry reaction tube, a magnetic stir bar was added followed by the monomer (1 mL, corresponding to 11.0 mmol (in the case of MA), 9.4 mmol (MMA), 8.7 mmol (Sty), or 10.9 mmol (VAc)) and PhIO (1 mol % vs. monomer, i.e., 0.11 mmol (24.2 mg) in the polymerizations of MA, 0.094 mmol (20.7 mg) (MMA), 0.087 mmol (19.4 mg) (Sty), or 0.109 mmol (24.0 mg) (VAc)). The tube was capped with a pre-washed with acetone rubber septum, secured with electric tape, and was then wrapped with aluminum foil to prevent the exposure of the contents to light. The dry solvent (DMAc or PhCl; 1 mL) was then injected and the tube was placed in an ice-water cooling bath in order to minimize evaporation of the reaction components during the following purging with nitrogen. The reaction mixture was deoxygenated by purging with nitrogen, which was introduced using a Teflon-coated needle, for 10 min. The tube was immersed in a water bath at 30 °C. After this, TMSX (X = N$_3$ or NCO; 2 eq vs. PhIO) was added using a micro syringe. The heterogeneous mixture rapidly became homogenous. At timed intervals, samples (ca. 0.08 mL) were withdrawn from the reaction mixture with a nitrogen-purged syringe, equipped with a Teflon-coated needle. Part of the sample was diluted with CDCl$_3$ (for NMR analysis) and part – with THF (for SEC analysis). Similar experiments were carried out using different amounts of PhIO (0.2-4 mol % vs. monomer) and TMSX (2 eq vs. PhIO) in DMAc. The polymers thus prepared contained one or more (x) (pseudo)halide groups X and are designated polyStyX$_x$, polyMMAX$_x$,

polyVAcX$_x$, and polyMAX$_x$. PolySty(N$_3$)$_x$ and polyVAc(N$_3$)$_x$ were purified by re-precipitation of solutions of the polymer in methylene chloride into large excess of methanol-water mixture (4:1 (v/v)), which was repeated three times, followed by drying. PolyMMA(N$_3$)$_x$ and polyMA(N$_3$)$_x$ were purified by dialysis against acetone using a membrane with molecular weight cut-off of 1,000 Da (Spectrum Labs). The solvent was changed every 10-12 hours and this was repeated six times, and the polymer was obtained by evaporation of the solvent. The corresponding (iso)cyanate-containing polymers were precipitated from methylene chloride solutions in hexane.

Synthesis of polymers using the PhIO-KX (X = Br, N$_3$, or OCN) initiating system

In a 10-mL dry reaction tube, equipped with a magnetic stir bar, the monomer (1 mL, corresponding to 11.0 mmol in the case of MA or 9.36 mmol in the case of MMA), PhIO (1 mol % vs. monomer), and potassium (pseudo)halide (bromide, azide, or isocyanate; 2 eq vs. PhIO) were mixed. The tube was sealed with an acetone-washed and dried rubber septum, which was secured with electric tape, and wrapped with aluminum foil. Anhydrous DMAc (1.0 mL) was then added through the septum and the mixture (cooled in an ice-water bath) was deoxygenated by purging with nitrogen (introduced with a Teflon-coated needle) for 10 min. Then, the tube was transferred to a water bath at 30 °C. Samples (ca. 0.08 mL) were withdrawn periodically from the mixture with a nitrogen-purged syringe equipped with a Teflon-coated needle for analysis, as described above. Similar experiments were carried out at a lower ratio of initiator to monomer (0.2 mol % of PhIO and 2 eq of pseudohalide salt vs. PhIO). The purifications of the final products were carried out as described above.

Click reactions of the azide-containing polymers with Pg₂O

The nitrogen contents in the polymers prepared using the PhIO-TMSN$_3$ initiating system was first determined in order to know the amount of azide groups present in a given mass of polymer. In a 10-mL reaction tube containing a magnetic stir bar, the amount of azide-containing polymer containing 600 μmol of N, i.e., 200 μmol of azide (0.22 g (in the case of polySty(N$_3$)$_x$), 0.98 g (polyMA(N$_3$)$_x$), 1.14 g (polyMMA(N$_3$)$_x$), or 1.04 g (polyVAc(N$_3$)$_x$)) and CuBr (1.4 mg, 10 μmol, 5 mol % vs. azide groups), were added and the tube was capped with a pre-washed with acetone rubber septum, which was then secured with electric tape. The tube was evacuated and back-filled with nitrogen five times. Deoxygenated DMF (2.0 mL) was injected with a nitrogen-purged syringe, and the mixture was stirred until solution was formed. Then, deoxygenated Pg$_2$O (10.3 μL, 100 μmol, corresponding to 200 μmol of acetylene groups) was added using a nitrogen-purged micro syringe, and the solution turned yellow. The reaction mixture was stirred for 15 h at r.t., after which a small sample was taken, diluted with THF and analyzed by SEC.

Reactions of (iso)cyanate-containing polymers with 1,3-propylene diamine

In a 10-mL reaction tube containing a magnetic stir bar, polymer prepared using the PhIO-TMSNCO initiating system (0.50 g, corresponding to 54.95 μmol of polySty(NCO)$_x$, or 50 μmmol of polyVAc(NCO)$_x$) was added followed by DMF (1 mL). The reaction mixture was stirred until the polymer dissolved and then 1,3-propylenediamine (3.67 μL, 57.95 μmol in the case of polySty(NCO)$_x$ or 3.34 μL, 50 μmmol, in the case of polyVAc(NCO)$_x$) was added. The reaction tubes were capped, and the solutions were stirred for 15 h at r.t., after which samples were diluted in THF and analyzed by SEC.

2.4.   Conclusions

The combination of iodosylbenzene with various (pseudo)halides, including trimethylsilyl azide or cyanate as well as potassium azide, isocyanate, or bromide, affords unstable hypervalent iodine(III) compounds, most likely, $PhIX_2$ (X = (pseudo)halide), which rapidly decompose *in situ* to the corresponding (pseudo)halide radicals, even at moderate temperatures (30 °C). These radicals can initiate the polymerization of monomers such as styrene, acrylates and methacrylates, as well as vinyl esters, and (pseudo)halide-capped functional polymers are produced. In the cases of monomers with relatively low propagation rate coefficients (e.g., styrene and methyl methacrylate) and especially when the radical source (initiator) $PhIX_2$ is generated rapidly at comparatively high concentrations and is particularly unstable (e.g., X = azide), limiting monomer conversions were observed, in accordance with "dead-end" polymerization mechanism. The presence of (pseudo)halide groups in the prepared polymers (in some cases, plausibly not only at the chain ends, but also as pendant backbone functionalities) is proved by elemental analysis, IR spectroscopy, and by conducting coupling reactions with propargyl ether (in the case of azide-containing polymers) or 1,3-propylenediamine (in the case of (iso)cyanate-containing polymers). The PhIO-(pseudo)halide-based initiators reported in this work provide a straightforward one-step methodology for the direct (i.e., not requiring postpolymerization modifications) synthesis of functionalized macromolecules.

2.5. References

1. A. Bravo, F. Fontana, G. Fronza, F. Minisci and L. Zhao, *Journal of Organic Chemistry*, 1998, **63**, 254-263.

2. P. J. Stang and V. V. Zhdankin, *Chemical Reviews*, 1996, **96**, 1123-1178.

3. A. Bravo, F. Fontana, G. Fronza, F. Minisci and A. Serri, *Tetrahedron Letters*, 1995, **36**, 6945-6948.

4. H. a. S. Saltzman, J. G. , *Organic Syntheses*, 1963, **43**, 60.

5. J. V. Carey, P. A. Chaloner, K. Seddon and M. Taylor, *Journal of Chemical Research Synopses*, 1996, 156-157.

6. R. Kumar, Y. Cao and N. V. Tsarevsky, *J. Org. Chem.*, 2017, **82**, 11806-11815.

7. N. V. Tsarevsky, *J. Polym. Sci., Part A: Polym. Chem. *, 2010, **48**, 966-974.

8. H. Han and N. V. Tsarevsky, *Polym. Chem.*, 2012, **3**, 1910-1917.

9. H. Han and N. V. Tsarevsky, *Chem. Sci.*, 2014, **5**, 4599-4609.

10. A. M. Golub, H. Koehler and V. V. Skopenko, eds., *Chemistry of Pseudohalides*, Elsevier, Amsterdam, 1986.

11. A. S. Dneprovskii, E. V. Eliseenkov and T. G. Chulkova, *Russ. J. Org. Chem.*, 2005, **40**, 28-35.

12. T. Muraki, H. Togo and M. Yokoyama, *Rev. Heteroatom Chem.*, 1997, **17**, 213-243.

13. X. Wang and A. Studer, *Acc. Chem. Res.*, 2017, **50**, 1712-1724.

14. J. Brandrup, E. H. Immergut and E. A. Grulke, eds., *Polymer Handbook*, Wiley, New York, 1999.

15. K. Matyjaszewski and N. V. Tsarevsky, *Nature Chem.*, 2009, **1**, 276-288.

16. A. V. Tobolsky, *J. Am. Chem. Soc.*, 1958, **80**, 5927-5929.

17. B. V. Pavlov and G. V. Korolev, *Vysokomol. Soedin.*, 1959, **1**, 869-877.

18. S. Beuermann and M. Buback, *Prog. Polym. Sci.*, 2002, **27**, 191-254.

19. C. Barner-Kowollik and G. T. Russell, *Prog. Polym. Sci.*, 2009, **34**, 1211-1259.

20. C. H. Bamford, W. G. Barb, A. D. Jenkins and P. F. Onyon, *The Kinetics of Vinyl Polymerization by Radical Mechanisms*, Academic Press, New York, 1958.

21. L. J. Bellamy, *The Infra-Red Spectra of Complex Molecules*, Methuen, London, 2nd edition., 1958.

22.   J. E. Gurst, in *The Chemistry of the Azido Group*, ed. S. Patai, Interscience, London, 1971, pp. 191-202.

23.   N. V. Tsarevsky, *J. Polym. Sci.: Part A: Polym. Chem.*, 2010, **48**, 966-974.

24.   D. A. Ben-Efraim, in *The Chemistry of Cyanates and Their Thio Derivatives*, ed. S. Patai, Wiley, Chichester, 1977, vol. 1, pp. 191-236.

25.   J. H. Boyer and F. C. Canter, *Chem. Rev.*, 1954, **54**, 1-57.

26.   P. A. S. Smith, in *Open-Chain Nitrogen Compounds*, Benjamin, New York, 1966, vol. 2, pp. 211-256.

27.   G. L'Abbe, *Chem. Rev.*, 1969, **69**, 345-363.

28.   T. Sheradsky, in *The Chemistry of the Azido Group*, ed. S. Patai, Interscience, London, 1971, pp. 331-395.

29.   E. F. V. Scriven and K. Turnbull, *Chem. Rev.*, 1988, **88**, 297-368.

30.   S. Braese, C. Gil, K. Knepper and V. Zimmermann, *Angew. Chem. Int. Ed.*, 2005, **44**, 5188-5240.

31.   S. Braese and K. Banert, eds., *Organic Azides: Syntheses and Applications*, Wiley, Chichester, 2010.

32. C. Schilling, N. Jung and S. Braese, in *Organic Azides: Syntheses and Applications*, S. Braese and K. Banert, Wiley, Chichester, 2010, pp. 269-284.

33. H. C. Kolb, M. G. Finn and K. B. Sharpless, *Angew. Chem. Int. Ed.*, 2001, **40**, 2004-2021.

34. J.-F. Lutz, H. G. Boerner and K. Weichenhan, *Macromol. Rapid Commun.*, 2005, **26**, 514.

35. J.-F. Lutz, *Angew. Chem. Int. Ed.*, 2007, **46**, 1018-1025.

36. W. H. Binder and R. Sachsenhofer, *Macromol. Rapid Commun.*, 2007, **28**, 15-54.

37. D. Fournier, R. Hoogenboom and U. S. Schubert, *Chem. Soc. Rev.*, 2007, **36**, 1369-1380.

38. M. Meldal and C. W. Tornoe, *Chem. Rev.*, 2008, **108**, 2952-3015.

39. R. K. Iha, K. L. Wooley, A. M. Nystrom, D. J. Burke, M. J. Kade and C. J. Hawker, *Chem. Rev.*, 2009, **109**, 5620-5686.

40. B. S. Sumerlin and A. P. Vogt, *Macromolecules*, 2010, **43**, 1-13.

41. K. A. Jensen and A. Holm, in *The Chemistry of Cyanates and Their Thio Derivatives*, ed. S. Patai, Wiley, Chichester, 1977, vol. 1, pp. 569-618.

42. R. Richter and H. Ulrich, in *The Chemistry of Cyanates and Their Thio Derivatives*, S. Patai, Wiley, Chichester, 1977, vol. 2, pp. 619-818.

43. A. M. Golub, H. Koehler and V. V. Skpenko, in *Chemistry of Pseudohalides*, eds. A. M. Golub, H. Koehler and V. V. Skpenko, Elsevier, Amsterdam, 1986, pp. 186-238.

44. H. Saltzman and J. G. Sharefkin, *Org. Synth.*, 1973, Coll. Vol. 5, 658-659.

CHAPTER 3.

SYNTHESIS OF LINEAR POLYMMA USING 1-CHLORO-1,2-BENZIODOXOL-3(1H)-ONE

3.1. Introduction

3.1.1. Heterocyclic HV iodine(III) compounds

On the basis of the available literature data, it can be stated that iodine is not capable of forming conjugated cyclic systems with aromatic stabilization because of the large atom size (hence poor orbital overlap) and the semi-ionic nature of the hypervalent I−N, and I−O bonds.[1] Moreover, the high level computational studies using adaptive natural density partitioning bond modeling technique reveal that the double bond between iodine atom and other elements does not exist.[2] Despite the lack of aromatic conjugation, five-membered heterocyclic iodine compounds have considerably higher thermal stability as compared to the noncyclic analogues due to the bridging of the equatorial HV bonds and the apical positions, covalent bonds, at HV iodine(III) center by a five-membered ring,[3] and also due to the better overlapping of the nonbonding electrons on HV iodine(III) atom with the π-orbitals of the benzene ring.[4] High thermal stability of five-membered I-O heterocycles (benziodoxoles) made possible the preparation of HV iodine(III) derivatives with exocyclic I−F,[5] I−Br,[6, 7] I−N$_3$,[8] I−CN,[9] and I−CF$_3$ bonds,[10] the linear analogues of

which are unstable. These substituted benziodoxoles have found applications as "atom-transfer" reagents for organic synthesis.[11] The most important heterocyclic λ^3-iodanes are represented by five-membered heterocycles, although several examples of four-membered and six-membered heterocycles with iodine(III) atom in the ring have also been reported. The five membered iodine(III) heterocycles are represented by various cyclic compounds[12, 13] incorporating HV iodine(III) and oxygen, nitrogen, or some other elements in the ring. Particularly important are the five-membered heterocyclic iodine compounds[12] with an oxygen atom in the ring, the so-called "benziodoxoles".

3.1.2. Structures and derivatives of benziodoxole (BIO)

X-ray single crystal structures have been reported for various benziodoxole derivatives, benziodazoles,[5, 14-16] benziodoxaboroles,[17] benziodoxathioles,[18, 19] and cyclic phosphonate.[20] In general, benziodoxoles have a planar structure with a highly distorted T-shaped geometry around iodine. The I−O bond length in the cycle of benziodoxolones (**1**, 2X = O) can vary from 2.11 Å in a benzoate derivative (**1**, Y = 3-ClC$_6$H$_4$CO$_2$)[21] to 2.48 Å in arylbenziodoxolone (**1**, Y = Ph),[22] which is indicative of a significant increase in the ionic nature of this bond. In the latter case, the bond length is consistent with iodonium salt structure. The observed bond angle C−I−O in benziodoxoles is about 80°, which is different from the 90° angle typical of noncyclic hypervalent iodine compounds.
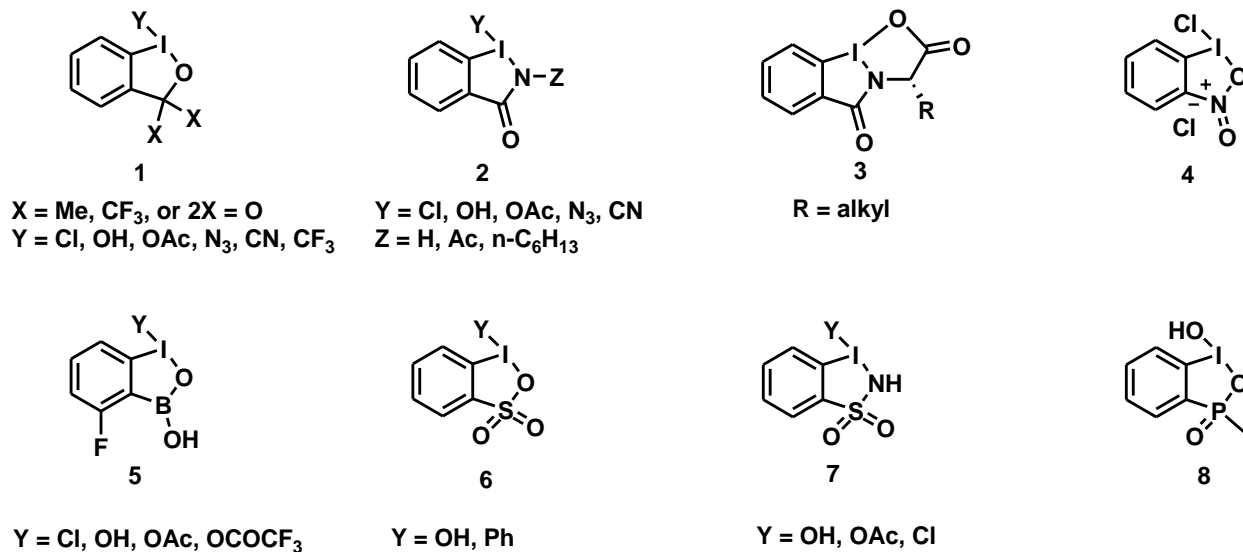
Scheme 3-1. Specific examples of hypervalent iodine(III) five-membered heterocycles.

Cyanobenziodoxoles (**1**, 2X = O and Y = CN) are thermally stable, white, microcrystalline solids; their structures of these compounds were confirmed by X-ray diffractometry. Cyanobenziodoxoles are useful cyano transfer reagents.[9, 23, 24] Waser and co-workers have reported the synthesis of thiocyanates by treatment of aliphatic and aromatic thiols with CNBIO at room temperature.[23] The cyclic N3BIO (**1**, 2X = O and Y = N₃), Zhdankin's reagent,[25] are thermally stable, microcrystalline solids, which can be stored indefinitely long in a refrigerator. Zhdankin's reagent can be readily prepared by the reaction of appropriate benziodoxoles with trimethylsilyl azide or sodium azide in good yields, and the corresponding structure was determined by single-crystal X-ray diffraction.[8, 26] Zhdankin's reagent are extensively used as efficient electrophilic or radical azidating reagents toward various organic substrates.[27] AcBIO[28] and methoxybenziodoxole[29] are stable compounds, which have been used as reagents in oxidation reactions.

Togo and co-workers reported the oxidation of alcohols to aldehydes or ketones using various acetoxybenziodoxole derivatives (**Scheme 3-1**).[28] Togni and co-workers have reported the synthesis of stable electrophilic trifluoromethylating reagents, trifluoromethylbenziodoxoles, by treatment of the corresponding methoxybenziodoxole or acetoxybenziodoxole with trimethyl(trifluoromethyl)silane.[10, 30] Solid-state structures of trifluoromethylbenziodoxoles were characterized by X-ray crystallography, which showed the distorted T-shaped geometry around iodine, typical for the hypervalent λ^3-iodanes.[31, 32] The chemistry of trifluoromethylbenziodoxoles has been summarized in a recent review by Togni and co-workers.[10]

Another very interesting heterocyclic HV iodine(III) compound, 1-chloro-1,2-benziodoxol-3-one, (**1**, 2X = O and Y = Cl) discovered in the middle of 20th century,[33] found to be very stable towards thermal and hydrolysis conditions. It is a well reputed oxidant[34, 35] and chlorine transfer reagent.[36, 37] Unfortunately, very few articles are available that describe its utility as oxidant and Cl-transfer agents compared to other cyclic HV iodine(III) reagents.

In this chapter, a series of heterocyclic HV iodine(III) compounds, including AcBIO, AzBIO and chloro benziodoxolone (ClBIO) were synthesized and employed as initiators in the polymerization of MMA.
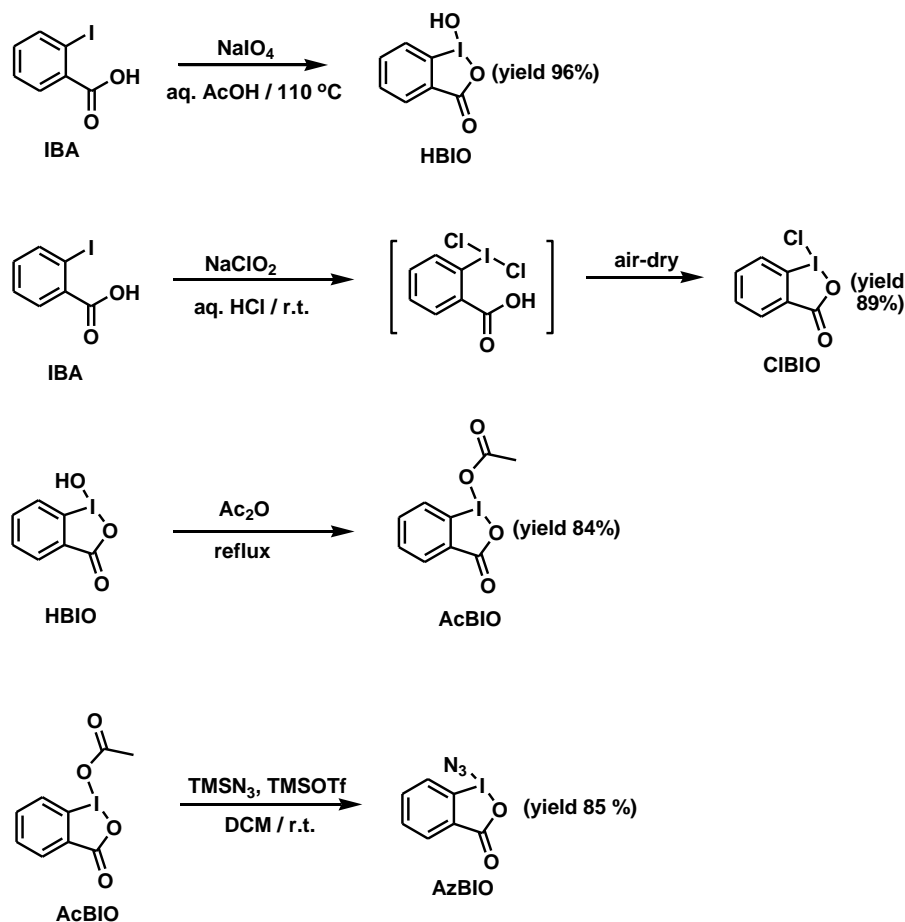
Scheme 3-2. Synthesis of various HV iodine(III) compounds like, HBIO, ClBIO, AcBIO and N₃BIO.

The HV iodine(III) compounds shown in **Scheme 3-2** contain weak hypervalent bonds, such as I-O, I-N₃, I-Cl, which can be cleaved homolytically upon heating or irradiation generating functional radicals like CH₃COO₂˙ (or CH₃˙, after decarboxylation), Cl˙, and N₃˙, utilized extensively in transformation of small organic molecules or employed to initiate radical polymerization.[38-41] The resulting polymers contain functionalities such as Cl˙ or N₃˙ at the α-terminus, which could be used to further functionalize the polymer α-chain end. at the α-chain end but, depending on the termination mechanism and the occurrence of transfer of (pseudo)halide groups from the initiator to the propagating radicals, also at the ω-chain end.

3.2. Results and Discussions

3.2.1. Synthesis and hydrolysis study of cyclic HV iodine(III) compounds

Cyclic HV iodine(III) derivatives are known for their radical reactions[18,19] and it was reasoned that they could be utilized to initiate the radical polymerization of vinyl monomers, such as MMA. These cyclic HV iodine(III) compounds are known for their stability and based on the literature, they can be easily synthesized and confirmed by NMR spectroscopy. The starting material for these cyclic HV iodine(III) is a commercially available and inexpensive compound, 2-iodobenzoic acid (IBA), both HBIO and ClBIO were prepared by a one-step reaction with high yields and high purity[20,21]. HBIO was then utilized to prepare 1-(acetoxy)-1,2-benziodoxol-3(1H)-one (AcBIO) and 1-(azido)-1,2-benziodoxol-3(1H)-one (AzBIO).[22,23] DMSO-d_6 was used as the NMR solvent except for ClBIO, which could oxidize DMSO rapidly to the sulfone, so CDCl$_3$ was used instead.

AzBIO, as an alternative to the unstable (diazidoiodo)benzene, PhIN$_3$, is an excellent source of azide radicals and very promising to prepare azide-containing polymers.[16,19,24] It was confirmed that AzBIO could decompose to generate azide radicals under visible light, however, the compound was found to be very sensitive to water, which rapidly hydrolyzed to HBIO and HN$_3$. This severely affected the efficiency of initiation of polymerization and could probably explain the unusual phenomenon that a white precipitate always occurred in the polymerization of MMA when AzBIO was used as the initiator. To study the hydrolysis of AzBIO, a NMR study was carried out in darkness by reacting AzBIO (4.3×10^{-2} M) with deionized water (0, 5 eq. or 10 eq.) in deuterated DMSO-d$_6$. According to **Figure 3-1(a)** and **3-1(b)**, AzBIO was hydrolyzed very

quickly and afterwards an equilibrium was established between AzBIO and HBIO. The hydrolysis was also observed in the control, of which the deuterated solvent contained trace amount of water.

In addition to AzBIO, another heterocyclic HV iodine(III) compound, AcBIO, was also reactive to water. Similarly, HBIO was formed as the product of the hydrolysis. As shown in **Figure 3-2 (a)**, the hydrolysis was a little slower but more complete than that of AzBIO. An example is shown in Figure 9 (b), which illustrates the hydrolysis of AcBIO into HBIO. The hydrolysis studies of AzBIO and AcBIO were also conducted in dry MeCN-d_3, and, as expected, both compounds were hydrolyzed rapidly. Due to the hydrolyzed product, HBIO, could not dissolve well in MeCN, a comparison between solvents was not given.

Therefore, to seek a water-insensitive cyclic HV iodine(III)-derivative was important for polymerizations and further functionalization. Fortunately, ClBIO, which could be synthesized directly from IBA, proved inert to water and also effective as a radical initiator. A similar hydrolysis study ([ClBIO]$_0$ = 4.4×10^{-2} M, [H$_2$O]$_0$ = 2.2 M in MeCN-d_3) was carried out, and as a result, the chemical shifts of ClBIO did not change after 1 day in the dark. It was reported[20] that ClBIO could participate in radical-involved chlorination reactions, thus the homolytic cleavage of I-Cl HV bonds provided a route of generating Cl$^\bullet$ radicals to induce polymerization.
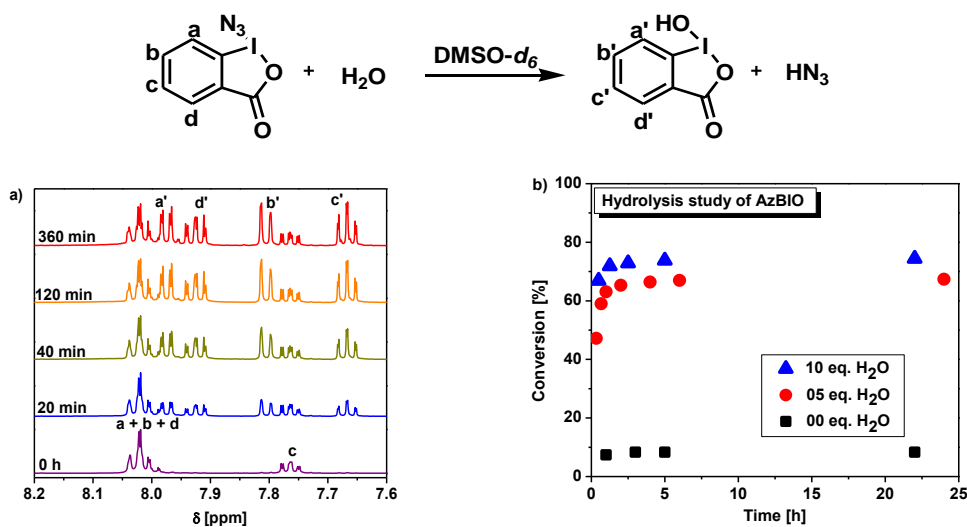
Figure 3-1. (a) NMR spectra showing the hydrolysis reaction of AzBIO ($[AzBIO]_0 = 4.3 \times 10^{-2}$ M, and $[H_2O]_0 = 2.1 \times 10^{-1}$ M) and (b) hydrolysis study of AzBIO: different amounts of deionized water (0, 5 eq. or 10 eq.) added to ABIO in DMSO-d_6 = 4.3×10^{-2} M in a dark NMR tube (b).
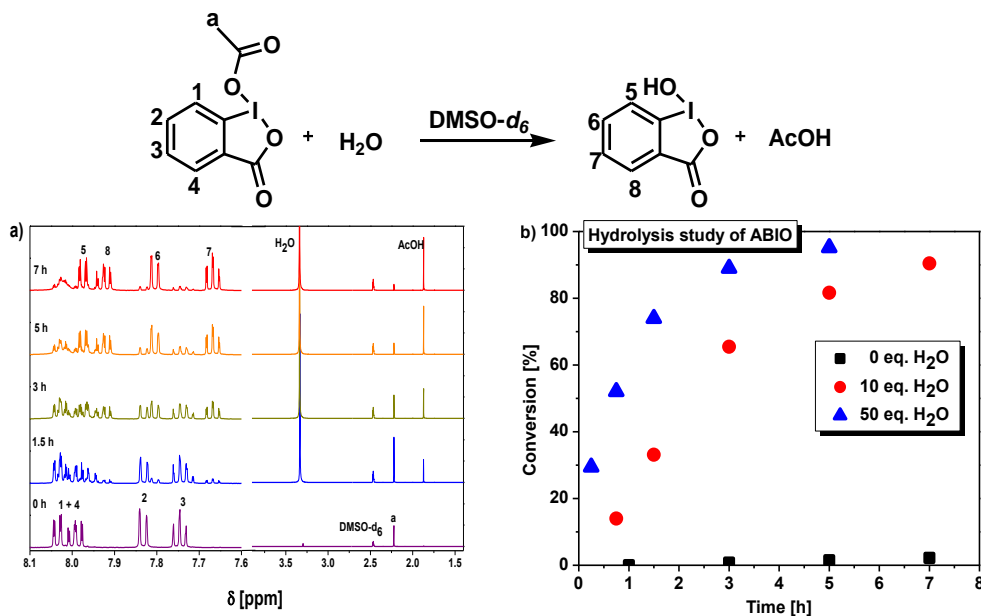
Figure 3-2 (a) NMR spectra showing the hydrolysis of ABIO ($[ABIO]_0 = 4.1 \times 10^{-2}$ M, and $[H_2O]_0$ = 4.1×10^{-1} M; the spectrum ranging from 8.7 to 7.5 ppm was enlarged for better visualization.) and (b) hydrolysis study of ABIO: different amounts of deionized water (0, 10 eq. or 50 eq.) added to ABIO in DMSO-d_6 (conc. = 4.1×10^{-2} M) in a dark NMR tube.

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3.3. Mechanism aspect of the polymerization of MMA using ClBIO

After the hydrolysis study, we concluded that ClBIO is compatible in the presence of water and hence chosen to be the candidate as the suitable radical initiator for the vinyl monomers such as MMA. Heterocyclic HV iodine(III) compounds of type (**2**, Y = Cl, **Scheme 3-1**) with I-Cl bonds[41] has been employed as potential radical initiators, where Cl• is shown to initiate polymerization of styrene with no significant living behavior. As illustrated in **Scheme 3-3**, a reaction mechanism, for the formation of radicals that might act as initiator or deactivator for the polymerization of MMA, might be assumed to involve the following key steps: (a) bond cleavage of the hypervalent iodine(III)-Cl bond of ClBIO generating Cl• and 9-I-2, iodanyl (iodinanyl) radical.[42, 43] and (b) where the Cl• could initiate the polymerization of MMA and in principal, the iodanyl radical could cap the chain ends since these radicals are stable enough to not generate new chains but due to the short lived nature of radicals it will couple with the propagating radical. The HV iodine(III)-based radicals and sterically hindered tertiary radicals are considered only as short-lived intermediates. However, under some conditions they may be present at higher concentrations and retardation is plausible.[44] Keeping these key points in mind we can anticipate a controlled system during the polymerization of MMA using ClBIO as initiators.
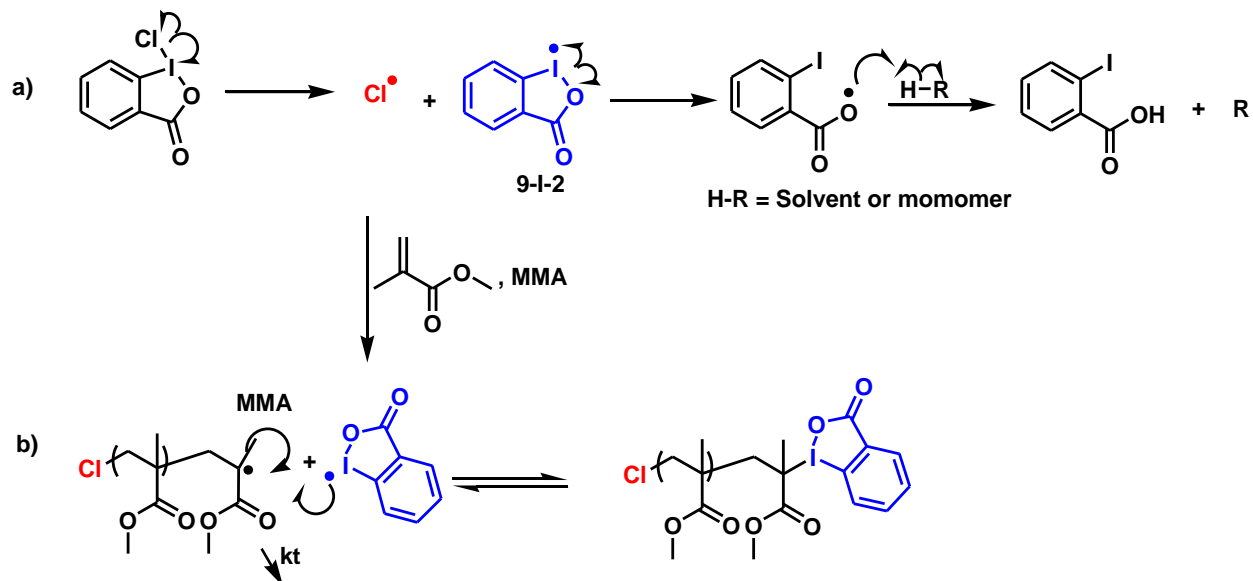
Scheme 3-3. Formation of Cl˙ and iodanyl (9-I-2) radicals under thermal conditions (a) and (b) the Cl˙ initiating the polymerization of MMA while the iodanyl radical reversibly deactivating the propagating radical.

3.3.1. Polymerization of MMA using ClBIO

ClBIO has very poor solubility in common organic solvents due to the benziodoxol ring and but has extremely high solubility in polar solvents like DMAc and hence, DMAc was chosen as the initial choice of solvent for the polymerization. To begin the investigation, MMA was polymerized in DMAc at 70 ^{0}C using ClBIO as the radical initiator with the degree of polymerization at complete monomer conversion $[MMA]_0/[ClBIO]_0$ set to 500 (**Figure 3-4**).
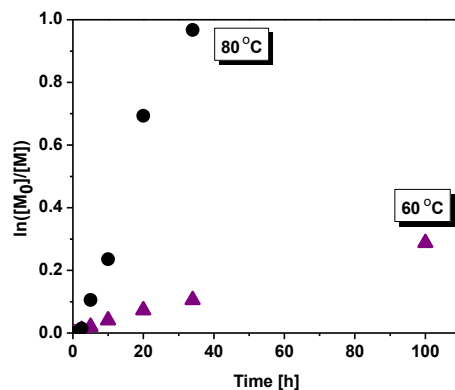
Figure 3-3. Temperature effect on the polymerization of MMA using ClBIO atratio $[MMA]_0$: $[ClBIO]_0 = 500$.
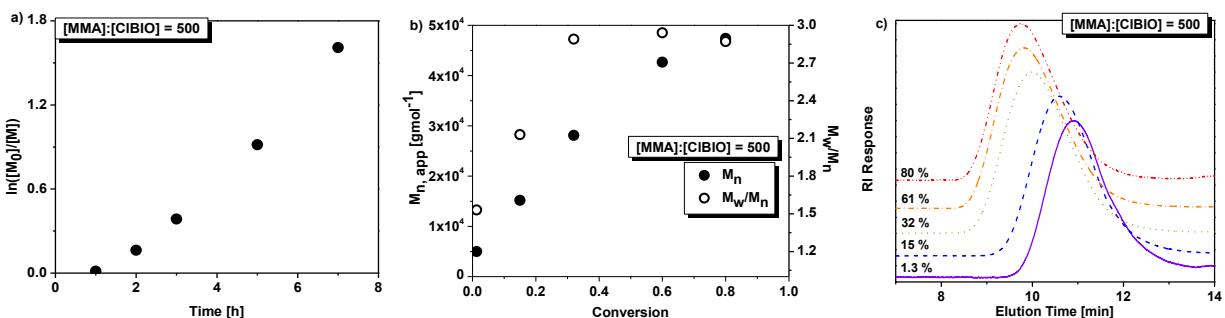
Figure 3-4. Polymerization of MMA (in DMAc, 1:1 (v/v)) using ClBIO ($[MMA]_0/[ClBIO]_0 = 500$) at 80 ^{0}C. a) Kinetics; (b) evolution of molecular weights and dispersities; and c) evolution of SEC traces of the polymers with monomer conversion (shown at each curve).

The monomer conversion was periodically determined by integrating the NMR signals of the vinyl and the solvent protons. This semilogarithmic plot is very sensitive to any change of the concentration of the active propagating species. A constant radical concentration is revealed by a straight line. A steady radical concentration in a living system is established by balancing the rates of activation and deactivation and not by balancing the rates of initiation and termination as in a conventional radical polymerization. As shown in **Figure 3-4 (a)**, the first-order kinetic plot was almost linear but with an upward curvature indicating an increase in radical concentration over

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time, which occurs in case of slow initiation. The polymerization was well-controlled, as indicated by the linear increase of $M_{n, app}$ with conversion [**Figure 3-4 (b)**]. The MWDs were rather broad but shifted smoothly towards higher molecular weights as the reactions proceeded [**Figure 3-4 (c)**], proving that the chosen HV iodine(III) (ClBIO) compound efficiently exchanged between propagating and dormant chains. The MWD dispersity was inevitable phenomena occurring during the polymerization.

High molecular weight functional polymers are desirable for many applications, and the limitation on the target degree of polymerization was explored next (**Figure 3-5**). At $DP_{n,targ} = 500$, relatively high conversion of 80 % could be reached in less than 8 h, and the polymers were very well-defined and shifted smoothly towards higher molecular weights as the reactions proceeded. Reaching this conversion was not possible when $DP_{n,targ}$ was increased to 4000, even after 48 h, because of the low initiator concentration. As shown in **Figure 3-5 (a)**, the kinetic rate gets slower as the initiator concentration is decreased that is at higher $DP_{n,targ}$. Whereas, as the $DP_{n,targ}$ is increased from 500 to 4000 the molecular weight increases as shown in **Figure 3-5 (b)**. The SEC traces, **Figure 3-5 (c)**, again revealed that the molecular weight distribution is wider that is higher polydispersity index and that can be attributed to the slow deactivation of the propagating chain ends. Nevertheless, well-defined polymers of relatively high molecular weights could be synthesized under the optimized reaction conditions.
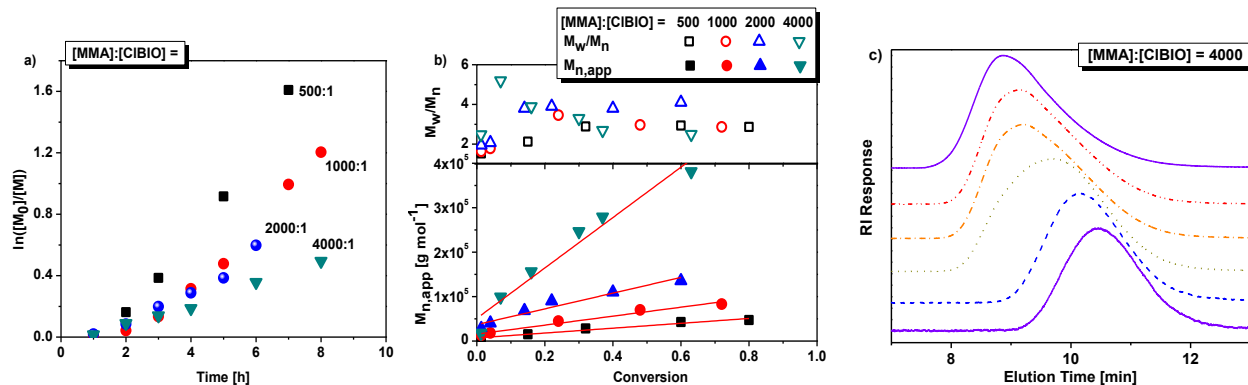
Figure 3-5. Polymerization of MMA (in DMAc, 1:1 (v/v)) using ClBIO ($DP_{n,targ}$ = 500, 1000, 2000, and 4000) at 80 ^{0}C. a) Kinetics; (b) evolution of molecular weights and dispersities with the theoretical MWs ; and c) evolution of SEC traces of the polymers ($DP_{n,targ}$ = 4000).

3.3.2. Solvent effect on the polymerization of MMA using ClBIO

In the retrospect of the previous results, our next attempts were to polymerize MMA using ClBIO ($DP_{n,targ}$ = 500) in various solvents and examine the living behavior. To our surprise, the rate of polymerization was significantly faster in DMAc (**Figure 3-6 (a)**) than in methyl isobutyrate (MIB, analogue to MMA structure) and in PhCl (relatively non-polar solvent) and also the polymerization was well-controlled, as indicated by the linear increase of $M_{n, app}$ with conversion in DMAc (**Figure 3-6 (b)**).

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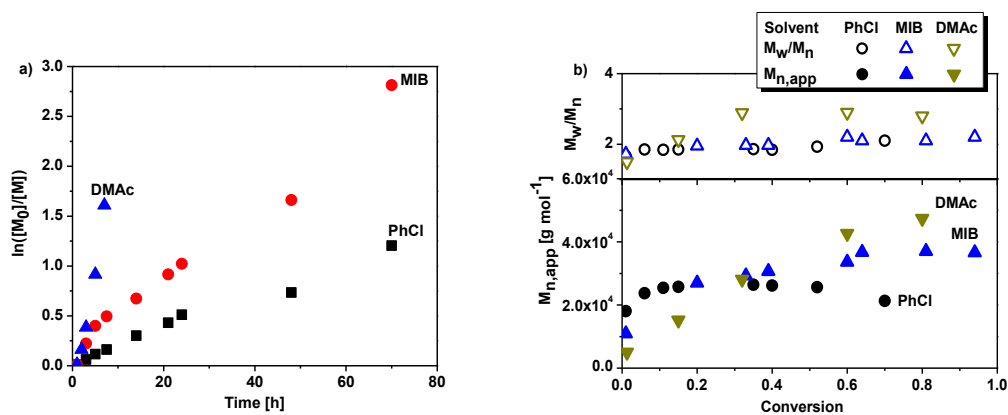
Figure 3-6. Polymerization of MMA (in DMAc, MIB, and PhCl in 1:1 (v/v)) using ClBIO ($DP_{n,targ}$ = 500) at 80 ^{0}C. a) Kinetics; (b) evolution of molecular weights and dispersities.

One of the most important advantages that controlled/"living" radical polymerization techniques offer is the ability to produce well-defined block copolymers through chain extension reactions. This is one of the ways to prove that there is a dormant species that could be activated under external stimuli. In this case to prove that the polyMMA chains are living in nature, i.e. caped with 9-I-2 (iodanyl) radical, a chain extension experiment was carried out by polymerizing MMA with the macroinitiator obtained from the polymerization of MMA using ClBIO with ($DP_{n,targ}$ = 500). To begin the investigation, MMA was polymerized in DMAc at 70 ^{0}C using macroinitiator ($M_{n,app}$ = 63,000 gmol^{-1}, obtained from SEC data) as the radical initiator with the degree of polymerization at complete monomer conversion ($DP_{n,targ}$ = [MMA]$_0$/[macro-initiator]$_0$) set to 1500 (**Figure 3-7**).
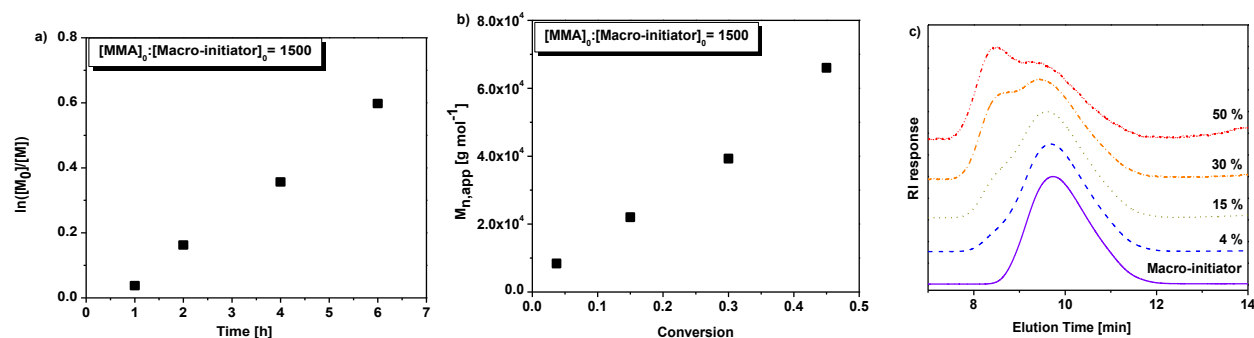
Figure 3-7. Chain extension of MMA using macroinitiator $DP_{n,targ} = [MMA]_0/[macro\text{-}initiator]_0$ set to 1500 in DMAc at 80 °C.

From the above data presented in **Figure 3-7 (c)** the chain extension revealed that the SEC traces for the polymers did not shift smoothly towards higher molecular weights as the reactions proceeded. Th bimodality was an indication of either some of the chain ends were dead while purification of macro-initiator since the chain end is essentially a HV iodine(III) moiety that is susceptible to external stimuli such as light, heat or any nucleophile (like MeOH). Or, there is another mechanism that could happen where instead of the coupling reaction between the propagating polymer radicals and 9-I-2 (as shown in **Scheme 3-3 (b)**), an irreversible transfer of Cl-atoms from ClBIO or Cl_2 (combination of two Cl-radicals) is evident (**Scheme 3-4**).
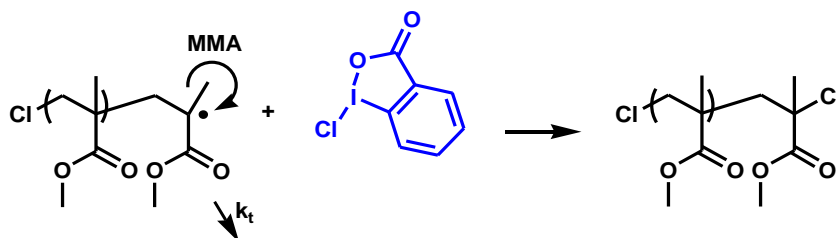
Scheme 3-4. Transfer of Cl-atoms to the propagating polymeric radicals.

3.4. Conclusions

In conclusion we have shown that ClBIO could be a potential candidate that can possibly control the synthesis of vinyl monomers such as MMA. The ratios between $[MMA]_0/[ClBIO]_0 =$ 500, 1000, 2000, and 4000 were carried out in DMAc at 80 ^{0}C and yielded polymers that were found to have a

3.5. Experimental Section

3.5.1. Materials

Methyl methacrylate (MMA, 99%, Aldrich) and ethylene glycol dimethacrylate (EGDMA, 97%, TCl) were purified before the experiments by passing the neat liquid through a column filled with basic alumina. The deuterated solvents (CDCl$_3$ (99.8% D) and DMSO-d$_6$ (99.9% D)) were purchased from Cambridge Isotope Laboratories, and a small amount of tetramethylsilane (TMS) was added as a chemical shift reference. 2-iodobenzoic acid (IBA, 98%, Acros), sodium chlorite (NaClO$_2$, 80%, Alfa Aesar), sodium periodate (NaIO$_4$, 99%, Acros), Bu$_3$P (95%, Alfa Aesar), CBr$_4$ (98%, Acros), trimethylsilyl azide (TMSN$_3$, 94%, Alfa Aesar), acetic acid (99.5%, Acros), acetic anhydride (99.1%, Fisher) and aqueous hydrochloric acid (37%, Aldrich) were used as received. Acetonitrile (MeCN, 99.8%, Aldrich) and N,N-dimethylacetamide (DMAc, 99.5%, Acros) were dried over anhydrous sodium sulfate powder for at least 12 h prior to use. All other solvents including acetone (99.5%, EMD Millipore), anhydrous ether (98%, EMD Millipore), petroleum ether (technique grade, EMD Millipore) and tetrahydrofuran (THF, 99%, Fisher) were used as received.

3.5.2. Analyses and equipment

Molecular weights and molecular weight distribution dispersities (M_w/M_n) were determined by size exclusion chromatography (SEC) on a Tosoh EcoSEC system equipped with a series of 4 columns (TSK gel guard Super HZ-L, Super HZM-M, Super HZM-N, and Super HZ2000) and using refractive index (RI) and UV detectors. THF was used as the eluent at a flow rate of 0.35 mL min^{-1} (40 °C). The SEC calibration was based on linear polystyrene standards. Monomer conversions were determined by ^{1}H NMR spectroscopy using a Bruker Avance DRX 400.

3.5.3. Synthetic procedures

Synthesis of hydroxyl-benziodoxole (HBIO)

NaIO$_4$ (7.24 g, 33.8 mmol), 2-iodobenzoic acid (8.0 g, 32.2 mmol), and aqueous acetic acid solution (30 vol%, 50 mL) were added to a 250 mL round bottom flask equipped with a magnetic stir bar. The mixture was rigorously stirred and refluxed at 110 °C for 4 h. The mixture was then diluted with cold deionized water (100 mL) and allowed to cool down to r.t. The flask was wrapped with aluminum foil to prevent light. White crystals were gradually formed, and after 1 h, the solids were collected by filtration, washed with ice water (3 × 20 mL) and acetone (3 × 20 mL) and finally dried under vacuum in darkness. The final product was obtained as a white crystal (8.17 g, 96.1%).

Synthesis of acetoxy-benziodoxolone (ABIO)

The above-mentioned HBIO (8.17 g, 30.9 mmol) was added to acetic anhydride (40 mL) in a 100 mL round bottom flask equipped with a magnetic stir bar. The flask was equipped with a

condenser. The flask was transferred into a preheated oil bath at 140 °C. After *ca.* 20 min, the mixture turned into a clear homogenous solution. The reaction solution was heated for another 5 mins and then allowed to cool to r.t. *Note*: the flask was wrapped with aluminum foil to prevent light. The flask was then put into a refrigerator at -18 °C for recrystallization. Finally, the product was filtered, washed with anhydrous ether, and dried under vacuum to yield a white crystal (8.0 g, 84.6%).

Synthesis of azido-benziodoxolone (AzBIO)

HBIO (0.53 g, 2 mmol) and $TMSN_3$ (0.53 mL, 4 mmol) were added to dry MeCN (20 mL) in a 100 mL round bottom flask equipped with a magnetic stir bar. The flask was capped with a clean rubber septum and the mixture was stirred overnight at r.t. The next day (after *ca.* 20 h), a clear pale-yellow solution had formed which indicated the formation of AzBIO. The solvent was removed by a rotary evaporator to give the crude product. After washing with anhydrous ether and followed by filtration and drying in air, a light-yellow solid was obtained (0.32 g, 56.2%).

Synthesis of chloro-benziodoxolone (ClBIO)

2-Iodobenzoic acid (2.48 g, 10 mmol) and $NaClO_2$ (3.38 g, 30 mmol) were dissolved in deionized water (50 mL) in a round bottom flask equipped with a magnetic stir bar. Concentrated aqueous HCl (20 mL) was added to the stirred solution dropwise over 10 min at r.t. During addition of the acid, the solution turned yellow. The flask was capped with a clean rubber septum and wrapped with aluminum foil to prevent light. The reaction was stirred for another 16 h at r.t. After that, the reaction mixture was filtered to collect the yellow solid. The solid was then washed with

deionized water and petroleum ether and dried under vacuum. A pale-yellow powder was obtained (2.5 g, 88.5%).

Hydrolysis study of ABIO and AzBIO

The hydrolysis study of AzBIO is described here as an example. AzBIO (10 mg, 3.46×10^{-5} mol) was dissolved in deuterated DMSO (0.8 mL) in a dark NMR tube, and certain amount of deionized water was added, *e.g.*, 6 µL (10 eq.), 3 µL (5 eq.) and no water added as the control. The NMR tubes were covered with a cap and sealed with parafilm. The NMR tubes were shaken at r.t. and analyzed periodically by NMR spectroscopy. Hydrolysis conversion was calculated based on the decrease of the integrals at the specific chemical shift of AzBIO as well as the appearance of new chemical shifts from the hydrolyzed product HBIO.

3.5.4. Preparation of linear polyMMA by using ClBIO as radical initiator.

ClBIO (29.0 mg, 0.1 mmol), MMA (1.0 mL, 9.35 mmol) with a magnetic stir bar were added to a cleaned and overnight dried 10 mL reaction tube. The tube was wrapped with an aluminum foil (to avoid any vis-light interactions) and capped with a rubber septum (soaked in acetone for two days and dried overnight) and through the septum, anhydrous DMAc (1.0 mL) was added. The mixture was purged with nitrogen for 15 mins using a special teflon coated needle (to prevent any oxidation reaction of ClBIO on the surface of regular steel needle) in an ice bath. A zero sample was withdrawn using a nitrogen purged syringe with teflon coated needle and then transferred the tube into an oil bath preheated to 80 °C to start the polymerization. Samples (ca.

0.2 mL) were periodically withdrawn with a nitrogen-purged syringe to monitor the monomer conversion, the apparent molecular weights, and molecular weight distributions of the polymers. The tube was wrapped with an aluminum foil (to avoid any vis-light interactions) and capped with a rubber septum (soaked in acetone for two days and dried overnight) and through the septum, anhydrous DMAc (1.0 mL) was added. The mixture was purged with nitrogen for 15 mins using a special teflon coated needle (to prevent any oxidation reaction of ClBIO on the surface of regular steel needle) in an ice bath. A zero sample was withdrawn using a nitrogen purged syringe with teflon coated needle and then transferred the tube into an oil bath preheated to 80 °C to start the polymerization. Samples (ca. 0.2 mL) were periodically withdrawn with a nitrogen-purged syringe to monitor the monomer conversion, the apparent molecular weights, and molecular weight distributions of the polymers.

3.6. References

1. V. V. Zhdankin, in *Hypervalent Iodine Chemistry*, Wiley, 2013.

2. A. S. Ivanov, I. A. Popov, A. I. Boldyrev and V. V. Zhdankin, *Angewandte Chemie International Edition*, 2014, **53**, 9617-9621.

3. R. L. Amey and J. C. Martin, *The Journal of Organic Chemistry*, 1979, **44**, 1779-1784.

4. G. F. Koser, in *Halides, Pseudo-Halides and Azides (1983)*, ed. S. Patai, Rappoport, Z., Wiley, 1983, vol. 1.

5. C. Y. Legault and J. Prévost, *Acta crystallographica. Section E, Structure reports online*, 2012, **68**, o1238-o1238.

6. A. K. Brisdon, *Annual Reports Section "A" (Inorganic Chemistry)*, 2002, **98**, 107-114.

7. D. C. Braddock, G. Cansell, S. A. Hermitage and A. J. P. White, *Chemical Communications*, 2006, 1442-1444.

8.   V. V. Zhdankin, C. J. Kuehl, A. P. Krasutsky, M. S. Formaneck and J. T. Bolz, *Tetrahedron Letters*, 1994, **35**, 9677-9680.

9.   Y.-F. Wang, J. Qiu, D. Kong, Y. Gao, F. Lu, P. G. Karmaker and F.-X. Chen, *Organic & Biomolecular Chemistry*, 2015, **13**, 365-368.

10.   J. Charpentier, N. Früh and A. Togni, *Chemical Reviews*, 2015, **115**, 650-682.

11.   J. P. Brand, D. F. González, S. Nicolai and J. Waser, *Chemical Communications*, 2011, **47**, 102-115.

12.   J. C. Lee, J. Y. Lee and S. J. Lee, *Tetrahedron letters*, 2004, **45**, 4939-4941.

13.   S. Schäfer and T. Wirth, *Angewandte Chemie International Edition*, 2010, **49**, 2786-2789.

14.   V. Nemykin, A. V Maskaev, M. R Geraskina, M. Yusubov and V. Zhdankin, *Preparation and X-ray Crystal Study of Benziodoxaborole Derivatives: New Hypervalent Iodine Heterocycles*, 2011.

15.   A. Yoshimura, S. R. Koski, J. M. Fuchs, A. Saito, V. N. Nemykin and V. V. Zhdankin, *Chemistry – A European Journal*, 2015, **21**, 5328-5331.

16.   M. Ochiai, T. Ito, Y. Masaki and M. Shiro, *Journal of the American Chemical Society*, 1992, **114**, 6269-6270.

17.   V. N. Nemykin, A. V. Maskaev, M. R. Geraskina, M. S. Yusubov and V. V. Zhdankin, *Inorganic Chemistry*, 2011, **50**, 11263-11272.

18.   G. F. Koser, G. Sun, C. W. Porter and W. J. Youngs, *The Journal of Organic Chemistry*, 1993, **58**, 7310-7312.

19.   A. Y. Koposov, D. N. Litvinov, V. V. Zhdankin, M. J. Ferguson, R. McDonald and R. R. Tykwinski, *European Journal of Organic Chemistry*, 2006, **2006**, 4791-4795.

20.   T. M. Balthazor, J. A. Miles and B. R. Stults, *The Journal of Organic Chemistry*, 1978, **43**, 4538-4540.

21.   J. Z. Gougoutas and L. Lessinger, *Journal of Solid State Chemistry*, 1974, **9**, 155-164.

22.   R. J. Batchelor, T. Birchall and J. F. Sawyer, *Inorganic Chemistry*, 1986, **25**, 1415-1420.

23.   R. Frei, T. Courant, M. D. Wodrich and J. Waser, *Chemistry – A European Journal*, 2015, **21**, 2662-2668.

24.   R. Chowdhury, J. Schörgenhumer, J. Novacek and M. Waser, *Tetrahedron letters*, 2015, **56**, 1911-1914.

25.   V. V. Zhdankin, S. A. Erickson and K. J. Hanson, *Journal of the American Chemical Society*, 1997, **119**, 4775-4776.

26.   G. A. Rabah and G. F. Koser, *Tetrahedron letters*, 1996, **37**, 6453-6456.

27.   V. V. Zhdankin, A. P. Krasutsky, C. J. Kuehl, A. J. Simonsen, J. K. Woodward, B. Mismash and J. T. Bolz, *Journal of the American Chemical Society*, 1996, **118**, 5192-5197.

28.   M. Iinuma, K. Moriyama and H. Togo, *European Journal of Organic Chemistry*, 2014, **2014**, 772-780.

29.   G. Shan, X. Yang, Y. Zong and Y. Rao, *Angewandte Chemie International Edition*, 2013, **52**, 13606-13610.

30.   P. Eisenberger, S. Gischig and A. Togni, *Chemistry – A European Journal*, 2006, **12**, 2579-2586.

31.   I. Kieltsch, P. Eisenberger and A. Togni, *Angewandte Chemie International Edition*, 2007, **46**, 754-757.

32.   N. Santschi, R. C. Sarott, E. Otth, R. Kissner and A. Togni, *Beilstein Journal of Organic Chemistry*, 2014, **10**, 1-6.

33.   L. J. Andrews and R. M. Keefer, *Journal of the American Chemical Society*, 1959, **81**, 4218-4223.

34.   X.-Q. Li and C. Zhang, *Synthesis*, 2009, **2009**, 1163-1169.

35.   V. Tiwari, V. N. Badavath, A. K. Singh and J. Kandasamy, *Tetrahedron letters*, 2018, **59**, 2511-2514.

36.   M. Wang, Y. Zhang, T. Wang, C. Wang, D. Xue and J. Xiao, *Organic Letters*, 2016, **18**, 1976-1979.

37.   H. Egami, T. Yoneda, M. Uku, T. Ide, Y. Kawato and Y. Hamashima, *The Journal of Organic Chemistry*, 2016, **81**, 4020-4030.

38.   H. Han and N. V. Tsarevsky, *Polymer Chemistry*, 2012, **3**, 1910-1917.

39.   H. Han and N. V. Tsarevsky, *Chemical Science*, 2014, **5**, 4599-4609.

40.   N. V. Tsarevsky, *J. Polym. Sci., Part A: Polym. Chem.* , 2010, **48**, 966-974.

41.   Y. Cao, R. Kumar and N. V. Tsarevsky, *Macromolecular Chemistry and Physics*, 2019, **0**, 1800471.

42.   M. Ochiai, T. Ito, H. Takahashi, A. Nakanishi, M. Toyonari, T. Sueda, S. Goto and M. Shiro, *Journal of the American Chemical Society*, 1996, **118**, 7716-7730.

43.   J. Gallos and A. Varvoglis, *Journal of the Chemical Society, Perkin Transactions 1*, 1983, 1999-2002.

44.   K. Matyjaszewski, in *Controlled/Living Radical Polymerization*, American Chemical Society, 2000, vol. 768, ch. 1, pp. 2-26.

CHAPTER 4.

SYNTHESIS OF BRANCHED POLYMERS USING 1-CHLORO-1,2-BENZIODOXOL-3(1H)-ONE

4.1. Introduction

4.1.1. Hyperbranched Polymers

Hyperbranched (HB) polymers, compared to the linear polymers, possess various advantages, such as highly branched topological structures, abundant functional groups, intramolecular cavities, low viscosity.[1-3] The application of HB polymers have been explored in various fields such as drug delivery, bioimaging, photoelectric materials, membranes, and coatings.[4-6] To date, polycondensation of AB_n-type monomers remains the predominate synthetic approach in the preparation of HB polymers.[7-14]
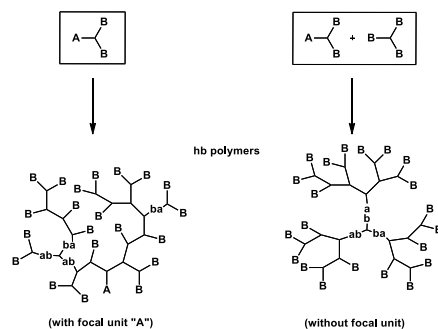
Scheme 4-1. Synthesis of HB using polycondensation of AB_n-type monomers.

Another popular method is self-condensing vinyl polymerization (SCVP) of inimer (containing monomer vinyl group and initiator fragment in one molecule).[15-19] It requires the use of controlled polymerization methods, such as controlled radical polymerization (CRP),[20-22] living ionic polymerization,[23-26] ring-opening metathesis polymerization (ROMP),[27] and group transfer polymerization[28] (as shown in **Scheme 4-2**).
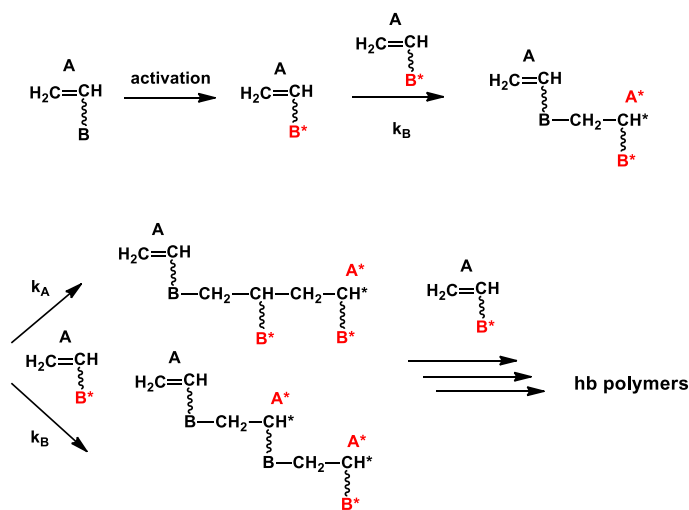
Scheme 4-2. Schematic representation of SCVP.

In both cases, the growth of HB polymers is accompanied by random polymer-polymer reactions in the continuous reaction media and finally results in polymers with extremely broad molecular weight distribution, which undermines the physical properties of HB polymers. Recently, one notable strategy for successful synthesis of HB polymers with high molecular weight and uniform structure was developed by carrying out one-pot polymerization of inimers in microemulsion.[29] Another very interesting synthetic approach, **Scheme 4-3**, in the preparation of HB polymers is the copolymerization of monovinyl monomers with divinyl or multivinyl crosslinkers in the presence of appropriate amounts of chain transfer agents (CTAs).
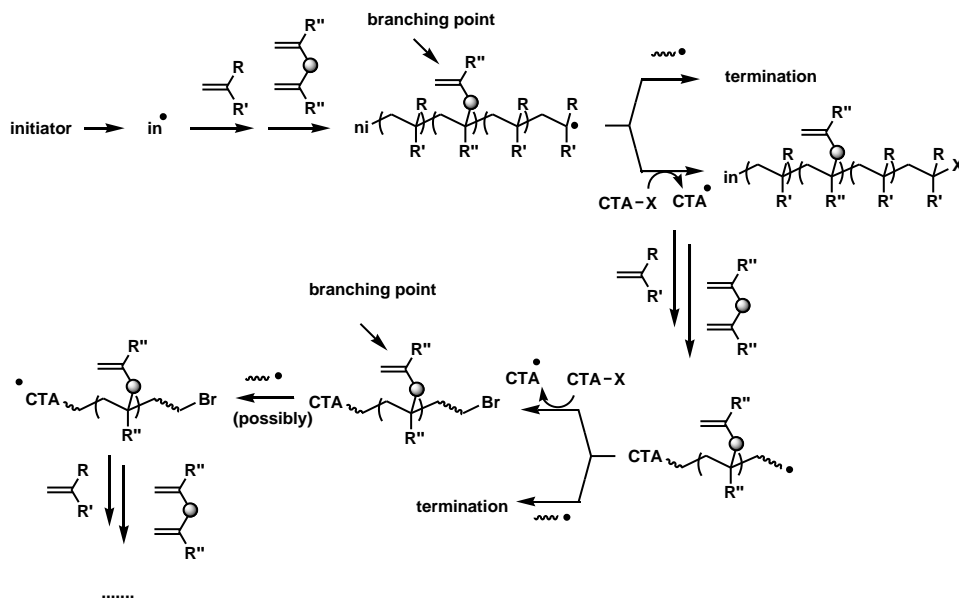
Scheme 4-3. Copolymerization of vinyl monomers with di-vinyl crosslinker in the presence of CBr₄ as CTA, yielding multi-brominated HB polymers.

The above strategy, **Scheme 4-3**, has been known for a relatively long time,[30, 31] and its utility has become more widely recognized and appreciated ever since the work of Sherrington and his collaborators.[32-34] The CTAs could be either a conventional transfer agent such a thiol,[32-34] carbon tetrabromide,[31, 35-37] or a controlling group that also imparts pseudo-livingness to the polymerization system.[38]

4.1.2. HV Iodine(III) Compounds as radical initiators

The HV iodine (III) compounds have attracted the attention of synthetic organic, theoretical, and materials chemists, and have been utilized as strong oxidants in organic synthesis, described in several research articles and review papers. Very limited number of HV iodine (III) compounds are known to undergo homolytic cleavage (upon heating or irradiation with light) of

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the hypervalent bonds and have been utilized in the polymerization of radically polymerizable monomers to yield directly functional polymers. For example, it was shown that the exchange of the acetoxy groups in (diacetoxyiodo)benzene with methacryloyloxy groups, formed branched polymers, via the *in-situ* formation of (dimethacryloyloxyiodo)benzene which served as monomer and as well initiators (i.e., as inimers). The generation of azide radicals by a ligand exchange reaction between (diacetoxyiodo)benzene and NaN_3 and their use in the synthesis of linear and branched polymers with azide functionalities at the chain ends were also reported. Another alternative approach demonstrated the use of iodosylbenzene, PhIO, to generate azide and other (pseudo)halide radicals that were employed to initiate polymerization of various monomers such as styrene, (meth)acrylates, and vinyl esters and were examined systematically for their scope and limitations in (pseudo)halide radical-initiated polymerizations. So far, the heterocyclic HV iodine (III) reagents have not been utilized as radical initiator into polymerization system because they often suffer from hydrolytically instability and limited solubility in common organic solvents. Thus, an alternative heterocyclic HV iodine (III) compounds with better stability towards hydrolysis and better solubility are highly desirable.

4.1.3. Iniferters in the preparation of HB polymers

Iniferters, proposed by Otsu in 1982,[34] are compounds that can mediate CRP. The term originates from the term's initiator, transfer and terminator. In principle, iniferters can induce radical polymerization which proceeds via dissociation, initiation, propagation, primary radical termination, and transfer to initiator. Typical iniferters include asymmetric azo compounds, tetraphenylethanes, sulfides and disulfides, dithiocarbamates, etc. The utilization of

dithiocarbamate compounds is of significant interest because the polymerization can proceed via a "living" radical polymerization mechanism due to the reversible coupling between propagating radicals and the CTA$^\bullet$ radicals.[35-39]

In fact, the chain transfer as well as (reversible) termination reactions involved in the iniferter polymerization can significantly affect the chain length of propagating polymers. Similar to the strategy by using CBr_4 as chain transfer agents,[40,41] the iniferter-initiated radical polymerization of vinyl monomers with the addition of a small amount of di- or multi-vinyl monomers can also produce hb polymers prior to gelation.[42,43] The limited polymer chain length and average number of incorporated pendant vinyl groups per chain greatly delay the crosslinking until moderate to high monomer conversions are reached. Without the further addition of additives such as chain transfer agents, the iniferter-initiated polymerization provides a facile method to prepare various hb polymers under FRP conditions, and importantly, afford polymers with specific chain end functionalities (originating from the iniferter).

In this chapter, a series of heterocyclic hypervalent iodine (III) compounds including ABIO, AzBIO and chloro benziodoxolone (ClBIO) were synthesized and employed as initiators in the polymerization of methacrylates. Since all these compounds contain weak hypervalent bonds, $e.g.$, I-O, I-N_3, I-Cl, which can be cleaved homolytically upon heating or irradiation, various functional radicals ($CH_3COO_2{}^\bullet$ (or $CH_3{}^\bullet$), $Cl^\bullet$, and $N_3{}^\bullet$) could be easily generated under suitable reaction conditions, and then employed to initiate radical polymerization. The resulting polymers contain a functionality at the α-terminus, which could be used to further functionalize the polymer α-chain end. In addition, ClBIO may serve as a CTA or iniferter in the polymerization of methacrylates under visible light irradiation. Although the polymerization did not follow a "living"

polymerization mechanism, significant transfer reactions were found based on the kinetic studies, and polymers with lower molecular weights were obtained when the amount of ClBIO in the mixtures was increased. With the addition of di-vinyl crosslinkers, hb polymers were successfully synthesized prior to gelation. The peripheral alkyl chloride groups were promising for further functionalizations.

4.2.   Results and Discussions
4.2.1.   Chain transfer coefficients

Dichloroiodoarenes ArICl$_2$ can easily transfer Cl atoms to carbon-centered radicals and some rate coefficients have been reported.[39] In this work, the ability of ClBIO, which contain a HV iodine(III) center and the labile I-Cl bond, to participate in chlorine transfer reactions with propagating radicals in polymerization reactions was examined. Our initial efforts were focused on determining chain transfer coefficients (C_{CTA}) of ClBIO in the polymerization of MMA. The classical Mayo equation (1)[40] was employed:

$$\frac{1}{DP_n} = \frac{1}{DP_{n,0}} + \frac{k_{tr}}{k_p}\frac{[CTA]}{[M]} = \frac{1}{DP_{n,0}} + C_{CTA}\frac{[CTA]}{[M]} \tag{1}$$

$DP_{n,0}$ and DP_n are respectively the number-average degrees of polymerization of a polymer obtained at low monomer (M) conversion in the absence and in the presence of a CTA (at concentration [CTA]). It was found that due to the thermal lability of ClBIO, it can initiate radical polymerization of MMA, Chapter 3, at temperatures exceeding 80 ºC. This is why, the experiments aimed at determination of the values of C_{CTA} were conducted at lower temperature (60 ºC), at which no appreciable initiation by ClBIO took place, especially during short (< 20 min) time

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periods (Chapter 3, **Figure 3-3**). In all cases, AIBN was used as the thermal initiator. For comparison purposes, the transfer coefficient of a well-known efficient CTA, which likewise transfers Cl atoms to C-centered radicals, CCl_4, was compared with the ClBIO. As shown in **Figure 4-1**, the chain transfer coefficient of ClBIO was determined to be 1.46 while that of CCl_4 was markedly lower ($C_{CTA}(CCl_4) = 0.012$, i.e., similar to the value reported in the literature, 0.0099[41, 42]).

Table 4-1. As the equivalents of ClBIO vs. AIBN increases the number-average molecular weight decrease.

#	Equivalents of ClBIO	Time (min)	Conversion [%]	$M_{n, app}$ [g mol^{-1}]
1	**0**	15	3	350,000
2	**2**	15	3	40,000
3	**4**	15	2	30,500
4	**6**	15	7	22,000
5	**8**	15	3	12,200
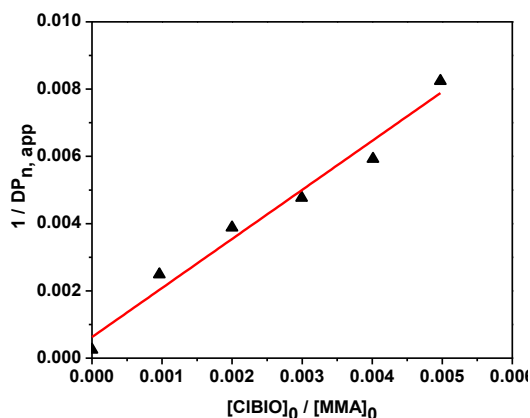
Figure 4-1. Mayo plots for the bulk polymerization of MMA in the presence of ClBIO at 60 °C. In all cases, the monomer conversions were below 5%. The raw data is provided in **Table 4-1**.

4.2.2. Preparation of hb polymers by using ClBIO as radical initiator

When divinyl crosslinkers are (co)polymerized, insoluble networks are formed usually extremely fast and at low monomer conversion, but the gelation can be significantly delayed by adding an efficient CTA to the reaction mixture; the extent, to which the formation of gel is delayed depends upon the concentrations of both the crosslinker and the CTA, as well as the efficiency of the latter. Prior to formation of crosslinked structures, soluble highly branched polymers are formed. At a fixed concentration of CTA, as the concentration of crosslinker increases, the degree of branching increases,[43] but also macroscopic gelation occurs earlier, i.e., at a lower conversion. Very highly branched polymers can still be obtained by using high fraction of crosslinker relative to the total monomer amount and even by homopolymerization of crosslinkers, but the CTA must be very efficient and/or used at high concentrations. HV iodine(III) compounds have been utilized as CTAs in the synthesis of branched polymers of styrene[42] but the measured high transfer coefficients (*vide supra*) for compounds with HV I-Cl bonds suggested that they indeed could be very useful, even when pure crosslinkers are polymerized. In particular, ClBIO was not only a very efficient CTA making it very suitable as additive in the copolymerization of MMA and EGDMA to afford branched functional polymers. The compound decomposes sufficiently fast at 80 °C and its decomposition products (Cl$^\bullet$ and the 9-I-2, **Scheme 4-1**) can initiate polymerization of MMA. The copolymerization of MMA and EGDMA initiated by ClBIO afforded, up to moderate to high conversions, Cl-capped HB polymers, which, in analogy with alkyl bromide-capped branched polymers reported in the literature, can be used for further chain-end functionalization reactions, such as nucleophilic substitution with azide followed by click coupling

with alkynes[44] or chain extension reactions under ATRP conditions to afford star polymers with branched cores.[44, 45]
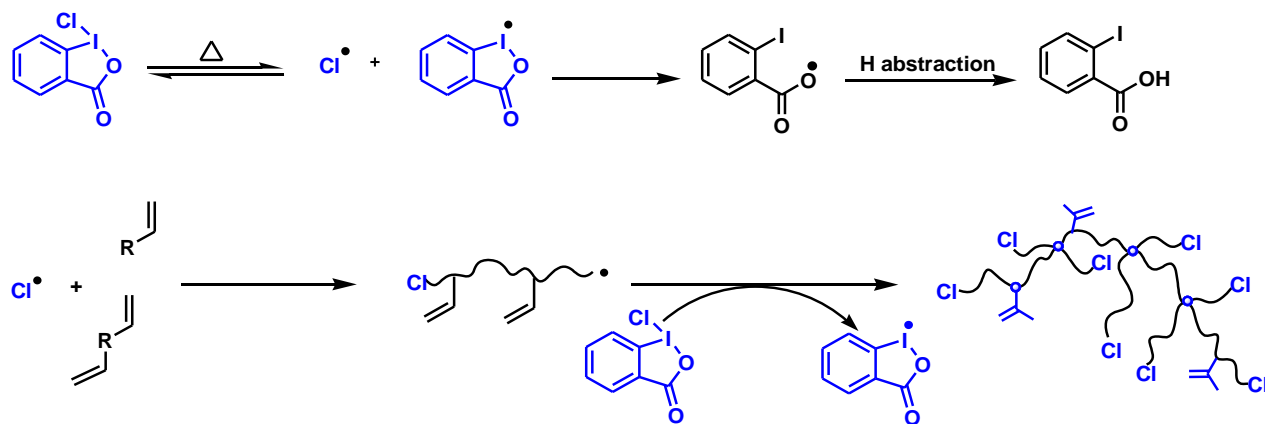
Scheme 4-4. Proposed mechanism for the formation of linear and branched polymers in radical copolymerization initiated by ClBIO, in which the same compounds served also as CTAs.

Initially, the effect of crosslinker amount on the branching and time of crosslinking was studied (**Table 4-2** and **Figures 4-2**). The concentration of ClBIO ([vinyl groups]$_0$ / [ClBIO]$_0$ = 100) was kept constant while the amount of EGDMA was varied from 10, 20, 40, 60, 80, to 100 mol % of the total vinyl groups. The polymerization rates were independent of the amount of EGDMA (**Figure 4-2(a)**). The apparent number average molecular weights ($M_{n, app}$) increased in an almost linear fashion with conversion and the molecular weight distributions (MWD) were broad, with the width increasing as the amount of EGDMA increased (**Figure 4-2(b)**), in accordance with the expected increase in the degree of branching.
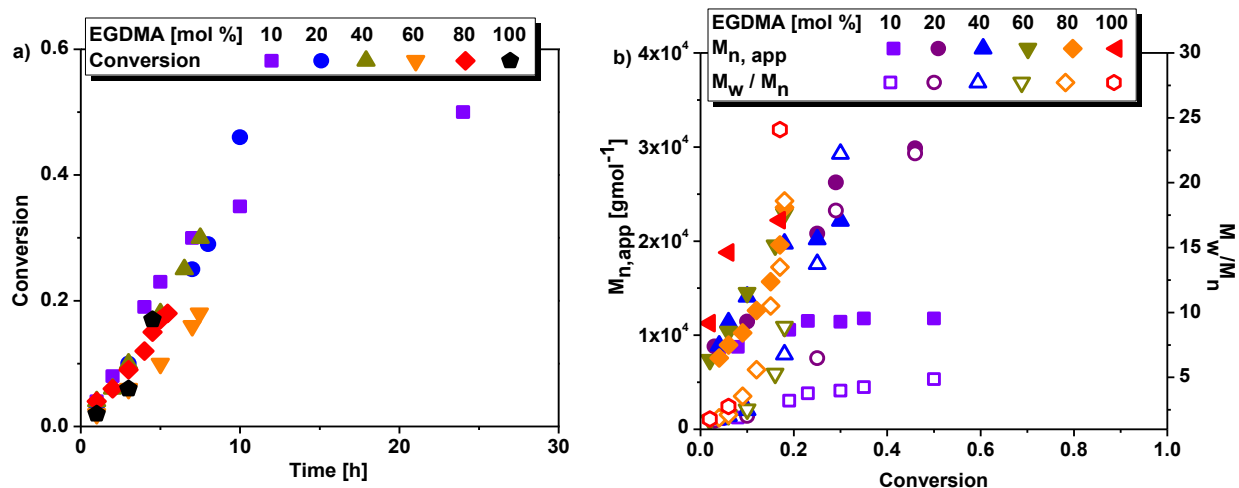
Figure 4-2. Copolymerization of MMA and EGDMA at 80 °C with ClBIO as initiator and CTA ([vinyl groups]$_0$ / [ClBIO]$_0$ = 100) and using 10, 20, 40, 60, 80, or 100 mol % EGDMA with respect to total vinyl groups: (a) kinetics; (b) evolution of molecular weights and M_w/M_n.

At almost the same vinyl group conversion (in the range 9-12 %), the value of the MWD dispersity ($Đ = M_w/M_n$) of the polymers formed in the reactions containing 10, 20, 40, 60, 80, and 100 mol % of EGDMA were 2.3, 2.7, 3.3, 5.4, 14.9, and 15.2, respectively as shown in **Table 4-2**. When pure EGDMA polymerized in the presence of ClBIO, gelation only occurred at 9 %, up to which point, soluble highly branched (and with high content of pendant vinyl group) polymers were formed (entry 6 in **Table 4-2**).

Table 4-2. Characteristics of HB polymers prepared using ClBIO as initiator and CTA in the copolymerization of MMA with EGDMA (at various amounts of EGDMA) at 80 °C.

#	EGDMA [mol%] [a]	Reaction time [h]	Conversion	$M_{n, app}$ [g mol^{-1}] [b]	M_w/M_n [b]
1	10	6	0.09	5,400	2.3
		32	0.41	12,500	15.3
		34	gel		
2	20	7	0.10	6,200	2.7
		22	0.34	15,000	17.2
		24	gel		
3	40	7	0.12	10,440	3.3
		14	0.24	17,300	11.2
		15	gel		
4	60	6	0.10	11,800	5.4
		9	0.16	16,350	19.1
		10	gel		
5	80	7	0.10	15,550	14.9
		7.5	gel		
6	100	6	0.09	14,930	15.2
		6.5	gel		

[a] Relative to the vinyl groups.
[b] Determined by SEC calibrated using linear polySty standards and equipped with an RI etector.

Next, the effect of the amount of ClBIO on the outcome of the polymerization was studied systematically (**Figure 4-3**). In the set of experiments summarized in **Table 4-3**, the amount of EGDMA was kept constant at 40 mol % relative to all vinyl groups, but the concentration of ClBIO was varied ([vinyl groups]$_0$ / [ClBIO]$_0$ = 25, 50, 100, 200, or 500).
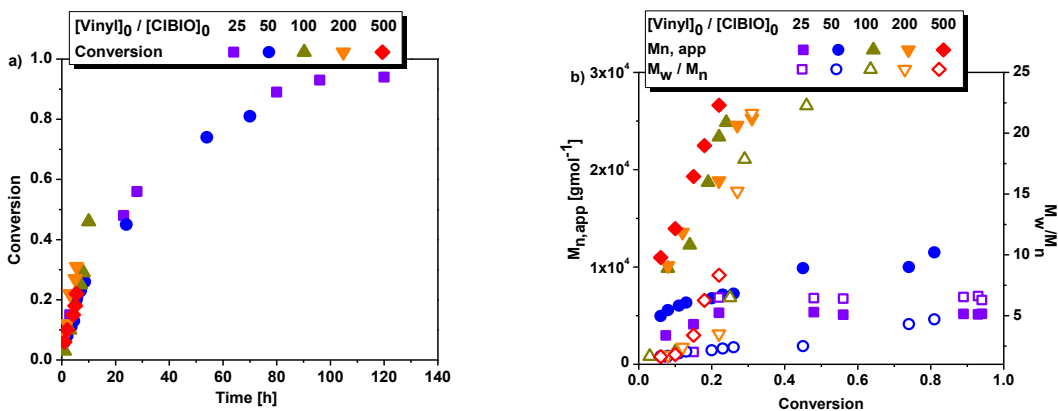
Figure 4-3. Copolymerization of MMA and EGDMA (40 mol %) at 80 °C in the presence of various amounts of ClBIO: (a) kinetics; (b) evolution of molecular weights and MWD dispersities.

The polymerization rates were virtually unaffected by the amount of ClBIO (**Figure 4-3(a)**). However, the amount of ClBIO impacted the MWD (**Figure 4-3(a)**): as the concentration of ClBIO increased, the MWDs became narrower. For instance, for the experiments where [vinyl groups]$_0$ / [ClBIO]$_0$ = 100, the value of Đ was 6.3 (at 14 % conversion) but as the concentration of ClBIO was doubled, the highly branched polymers had a narrower MWD (Đ = 5.5 at 15 % conversion), and when it was quadrupled, the MWD became narrower still (Đ = 3.8 at the same conversion), as seen in **Table 4-3** (entries 1–3). At higher concentrations of ClBIO, the formation of network was delayed to higher monomer conversions. Thus, at [vinyl groups]$_0$ / [ClBIO] = 400, macroscopic gelation was observed in less than 4 h at 10 % conversion but a 16-fold increase of the amount of ClBIO ([vinyl groups]$_0$ / [ClBIO] = 25) made it possible to form soluble branched polymers up to 30 % monomer conversion, which occurred in more than 12 h (**Table 4-3**).

Table 4-3. Characteristics of HB polymers prepared by the copolymerization of MMA and EGDMA (40 mol % of EGDMA) at 80 °C using various amounts of ClBIO.

#	[vinyl groups]$_0$ / [ClBIO]$_0$	Reaction time [h]	Conversion	$M_{n, app}$ [g mol^{-1}] [b]	M_w/M_n [b]
1	25	6	0.15	3,850	3.8
		12	0.30	7,400	20.1
		13	gel		
2	50	4	0.15	6,800	5.5
		9	0.22	9,260	23.6
		10	gel		
3	100	5	0.14	9,500	6.3
		7	0.18	14,000	16.5
		7.5	gel		
4	200	4	0.11	15,800	8.7
		5	0.13	16,800	12.2
		5.5	gel		
5	500	3	0.08	23,350	9.6
		4	0.10	27,800	21.1
		4.5	gel		

[a] Relative to the total vinyl groups.
[b] Determined by SEC calibrated using linear polySty standards and equipped with an RI detector.

These observations are consistent with the fact that at higher concentrations of ClBIO, shorter chains containing smaller number of pendant vinyl groups are formed, and thus the probability of each chain to serve as crosslinker connecting many other chains decreases, thus delaying gelation. Highly compact branched structures consisting of interconnected short polymer chains were most likely formed under these reaction conditions.

4.3.   Experimental Section

4.3.1.   Materials

Methyl methacrylate (MMA, 99%, Aldrich) and ethylene glycol dimethacrylate (EGDMA, 97%, TCl) were purified before the experiments by passing the neat liquid through a column filled with basic alumina. The deuterated solvents (CDCl$_3$ (99.8% D) and DMSO-d$_6$ (99.9% D)) were purchased from Cambridge Isotope Laboratories, and a small amount of tetramethylsilane (TMS) was added as a chemical shift reference. 2-iodobenzoic acid (IBA, 98%, Acros), sodium chlorite (NaClO$_2$, 80%, Alfa Aesar), sodium periodate (NaIO$_4$, 99%, Acros), Bu$_3$P (95%, Alfa Aesar), CBr$_4$ (98%, Acros), trimethylsilyl azide (TMSN$_3$, 94%, Alfa Aesar), acetic acid (99.5%, Acros), acetic anhydride (99.1%, Fisher) and aqueous hydrochloric acid (37%, Aldrich) were used as received. Acetonitrile (MeCN, 99.8%, Aldrich) and N,N-dimethylacetamide (DMAc, 99.5%, Acros) were dried over anhydrous sodium sulfate powder for at least 12 h prior to use. All other solvents including acetone (99.5%, EMD Millipore), anhydrous ether (98%, EMD Millipore), petroleum ether (technique grade, EMD Millipore) and tetrahydrofuran (THF, 99%, Fisher) were used as received.

4.3.2.   Analyses and equipment

Molecular weights and molecular weight distribution dispersities (M$_w$/M$_n$) were determined by size exclusion chromatography (SEC) on a Tosoh EcoSEC system equipped with a series of 4 columns (TSK gel guard Super HZ-L, Super HZM-M, Super HZM-N, and Super HZ2000) and using refractive index (RI) and UV detectors. THF was used as the eluent at a flow rate of 0.35 mL min^{-1} (40 °C). The SEC calibration was based on linear polystyrene standards.

Monomer conversions were determined by ^{1}H NMR spectroscopy using a Bruker Avance DRX 400.

4.3.3. Synthetic procedures

Synthesis of chloro benziodoxolone (ClBIO)

2-Iodobenzoic acid (2.48 g, 10 mmol) and NaClO$_2$ (3.38 g, 30 mmol) were dissolved in deionized water (50 mL) in a round bottom flask equipped with a magnetic stir bar. Concentrated aqueous HCl (20 mL) was added to the stirred solution dropwise over 10 min at r.t. During addition of the acid, the solution turned yellow. The flask was capped with a clean rubber septum and wrapped with aluminum foil to prevent light. The reaction was stirred for another 16 h at r.t. After that, the reaction mixture was filtered to collect the yellow solid. The solid was then washed with deionized water and petroleum ether and dried under vacuum. A pale-yellow powder was obtained (2.5 g, 88.5%).

4.3.4. Synthesis of HB polymers by copolymerization of MMA and EGDMA in the presence of ClBIO

In the following procedure, 40 mol % of EGDMA of the total vinyl groups and ClBIO (1 mol % vs. the total vinyl groups) were used. In a 10 mL reaction tube, a magnetic stir bar was added, followed by MMA (0.66 mL, 5.76 mmol), EGDMA (0.250 g, 1.92 mmol), and ClBIO (0.035 g, 9.59 mmol). The tube was capped with a rubber septum (pre-washed with acetone and dried), which was secured with electric tape, and the contents were protected from light by wrapping the tube with aluminum foil. Dry DMAc (1.34 mL) was then injected and the tube was

placed in an ice-water cooling bath, and the reaction mixture was deoxygenated by purging with nitrogen using a Teflon-coated needle for 10 min. The reaction tube was then placed in an oil bath preheated to 80 °C. At timed intervals, samples (ca. 0.04 mL) were withdrawn from the reaction mixture with a nitrogen-purged syringe equipped with a Teflon-coated needle to determine the monomer conversion (by NMR) and the molecular weights (SEC) of the polymers.

Similar experiments were conducted using the same amount of ClBIO ([vinyl groups]$_0$ / [ClBIO]$_0$ = 100), but varying amounts of EGDMA. The MMA and EGDMA amounts were: MMA (1 mL, 8.64 mmol) and EGDMA (0.063 g, 0.48 mmol) for [EGDMA]$_0$ = 10 mol % of the total vinyl groups; MMA (0.88 mL, 7.64 mmol) and EGDMA (0.125 g, 0.96 mmol) for [EGDMA]$_0$ = 20 mol % of the total vinyl groups; MMA (0.44 mL, 3.74 mmol) and EGDMA (0.374 g, 2.88 mmol) for [EGDMA]$_0$ = 60 mol % of the total vinyl groups; MMA (0.22 mL, 1.92 mmol) and EGDMA (0.499 g, 3.84 mmol) for [EGDMA]$_0$ = 80 mol % of the total vinyl groups; and pure EGDMA (0.624 g, 4.80 mmol, corresponding to 9.6 mmol of vinyl groups). In each case, the amount of DMAc used was changed so that the total volume of the reaction mixture was 2 mL.

When varying amounts of ClBIO relative to vinyl groups were used, the amounts of MMA (1 mL, 8.64 mmol), EGDMA (0.374 g, 2.88 mmol), and DMAc (1 mL) were kept constant while the amount of ClBIO was changed to 0.2102 g (0.576 mmol for [vinyl groups]$_0$ / [ClBIO]$_0$ = 25), 0.1051 g (0.288 mmol for [vinyl groups]$_0$ / [ClBIO]$_0$ = 50), 0.053 g (0.144 mmol for [vinyl groups]$_0$ / [ClBIO]$_0$ = 100), 0.026 g (0.072 mmol for [vinyl groups]$_0$ / [ClBIO]$_0$ = 200), or 0.013 g (0.036 mmol for [vinyl groups]$_0$ / [ClBIO]$_0$ = 400).

4.4. Conclusions

The heterocyclic HV iodine(III) compound, ClBIO with I-Cl bonds was found to be a very efficient chain transfer agents (CTAs) in the polymerization of MMA. The chain transfer coefficient was found to be markedly higher than those of a traditionally used CTA, CCl_4. At high temperatures, the HV iodine(III) compounds served simultaneously as efficient radical initiators and CTAs, which made them very suitable reactants for the synthesis of highly branched and chain-end functionalized (mostly Cl-capped) polymers when added to mixtures of MMA and a divinyl crosslinker, EGDMA. Due to the significant values of the chain transfer coefficients, the HV iodine(III) compounds could be used at relatively low concentrations (in some cases, less than 1 mol % vs. vinyl groups), even in copolymerizations in the presence of large concentrations of crosslinker, and still efficiently delay gelation up to moderate to high conversions and yield soluble highly branched end-functional polymers.

4.5.   References

1.   B. Voit, *J. Polym. Sci. Part A: Polym. Chem.*, 2000, **38**, 2505-2525.

2.   M. Jikei and M.-a. Kakimoto, *Prog. Polym. Sci.*, 2001, **26**, 1233-1285.

3.   B. I. Voit and A. Lederer, *Chem. Rev.*, 2009, **109**, 5924-5973.

4.   Q. Zhu, F. Qiu, B. Zhu and X. Zhu, *RSC Adv.*, 2013, **3**, 2071-2083.

5.   D. Wang, T. Zhao, X. Zhu, D. Yan and W. Wang, *Chem. Soc. Rev.*, 2015, **44**, 4023-4071.

6.   W. Wu, R. Tang, Q. Li and Z. Li, *Chem. Soc. Rev.*, 2015, **44**, 3997-4022.

7.   J. R. Schaefgen and P. J. Flory, *J. Am. Chem. Soc.*, 1948, **70**, 2709-2718.

8.   P. Bharathi and J. S. Moore, *J. Am. Chem. Soc.*, 1997, **119**, 3391-3392.

9.   D. H. Bolton and K. L. Wooley, *Macromolecules*, 1997, **30**, 1890-1896.

10.   D. Konkolewicz, A. Gray-Weale and S. Perrier, *J. Am. Chem. Soc.*, 2009, **131**, 18075-18077.

11. W. Huang, L. Su and Z. Bo, *J. Am. Chem. Soc.*, 2009, **131**, 10348-10349.

12. Z. Xue, A. D. Finke and J. S. Moore, *Macromolecules*, 2010, **43**, 9277-9282.

13. Y. Segawa, T. Higashihara and M. Ueda, *J. Am. Chem. Soc.*, 2010, **132**, 11000-11001.

14. B. Zhao, Y. Zheng, Z. Weng, S. Cai and C. Gao, *Polym. Chem*, 2015, **6**, 3747-3753.

15. J. M. J. Fréchet, M. Henmi, I. Gitsov, S. Aoshima, M. R. Leduc and R. B. Grubbs, *Science*, 1995, **269**, 1080-1083.

16. M. Liu, N. Vladimirov and J. M. J. Fréchet, *Macromolecules*, 1999, **32**, 6881-6884.

17. T. Zhao, Y. Zheng, J. Poly and W. Wang, *Nat Commun*, 2013, **4**, 1873.

18. H. Sun, C. P. Kabb and B. S. Sumerlin, *Chem. Sci.*, 2014, **5**, 4646-4655.

19. R. W. Graff, X. Wang and H. Gao, *Macromolecules*, 2015, **48**, 2118-2126.

20. C. J. Hawker, J. M. J. Frechet, R. B. Grubbs and J. Dao, *J. Am. Chem. Soc*, 1995, **117**, 10763-10764.

21. S. G. Gaynor, S. Edelman and K. Matyjaszewski, *Macromolecules*, 1996, **29**, 1079-1081.

22.   J. Chiefari, Y. K. Chong, F. Ercole, J. Krstina, J. Jeffery, T. P. T. Le, R. T. A. Mayadunne, G. F. Meijs, C. L. Moad, G. Moad, E. Rizzardo and S. H. Thang, *Macromolecules*, 1998, **31**, 5559-5562.

23.   M. Szwarc, *Nature*, 1956, **178**, 1168.

24.   M. Miyamoto, M. Sawamoto and T. Higashimura, *Macromolecules*, 1984, **17**, 265-268.

25.   D. Baskaran, *Macromol. Chem. Phys.*, 2001, **202**, 1569-1575.

26.   C. Paulo and J. E. Puskas, *Macromolecules*, 2001, **34**, 734-739.

27.   R. Grubbs and W. Tumas, *Science*, 1989, **243**, 907-915.

28.   O. W. Webster, W. R. Hertler, D. Y. Sogah, W. B. Farnham and T. V. RajanBabu, *J. Am. Chem. Soc.*, 1983, **105**, 5706-5708.

29.   K. Min and H. Gao, *J. Am. Chem. Soc.*, 2012, **134**, 15680-15683.

30.   C. Hui, I. Koji, F. Takashi and K. Toshio, *J. Polym. Sci. Polym. Chem. Ed.*, 1984, **22**, 2123-2130.

31.   H. Chen, Y. M. Won, K. Ishizu and T. Fukutomi, *Polym. J.*, 1985, **17**, 687.

32.   N. O'Brien, A. McKee, D. C. Sherrington, A. T. Slark and A. Titterton, *Polymer*, 2000, **41**, 6027-6031.

33.   P. A. Costello, I. K. Martin, A. T. Slark, D. C. Sherrington and A. Titterton, *Polymer*, 2002, **43**, 245-254.

34.   A. T. Slark, D. C. Sherrington, A. Titterton and I. K. Martin, *J. Mater. Chem.*, 2003, **13**, 2711-2720.

35.   H. Chen, K. Ishizu, T. Fukutomi and T. Kakurai, *J. Polym. Sci. Polym. Chem. Ed*, 1984, **22**, 2123-2130.

36.   D.-L. Popescu and N. V. Tsarevsky, *Macromol. Rapid Commun.*, 2012, **33**, 869-875.

37.   D.-L. Popescu and N. V. Tsarevsky, *Aust. J. Chem.*, 2012, **65**, 28-34.

38.   F. Isaure, P. A. G. Cormack, S. Graham, D. C. Sherrington, S. P. Armes and V. Bütün, *Chem. Commun.*, 2004, **9**, 1138-1139.

39.   A. S. E. Dneprovskii, E. V. Chulkova, T. G. , *Russ J Org Chem.*, 2005, **41**, 28-34.

40.   F. R. Mayo, *J. Am. Chem. Soc.*, 1943, **65**, 2324-2329.

41.   R. A. Gregg and F. R. Mayo, *J. Am. Chem. Soc.*, 1948, **70**, 2373-2378.

42. Y. Cao, R. Kumar and N. V. Tsarevsky, *Macromolecular Chemistry and Physics*, 2019, **220**, 1800471.

43. W. H. Li, A. E. Hamielec and C. M. Crowe, *Polymer.*, 1989, **30**, 1518-1523.

44. D.-L. Popescu and N. V. Tsarevsky, *Aust. J. Chem.*, 2012, **65**, 28-34.

CHAPTER 5.

HV IODINE(III) COMPOUNDS WITH TETRAZOLE LIGANDS

5.1. Introduction

5.1.1. HV iodine(III) compounds containing I-N bonds

HV iodine(III) compounds containing I-N bonds were first reported in 1983 by Varvoglis.[1,2] Subsequently, different HV iodine(III) compounds with I-N bonds, such as azidoiodanes[3–8], benziodazoles[9,10], and iminoiodanes[11–15] were investigated as efficient reagents for C-N bond forming reactions. These reagents have been utilized in the direct Azidation,[5,8,16] amination,[12,16,18–23] aziridination,[13,14] and C-H insertion reactions.[23,24] Furthermore, there are very few examples of HV iodine(III) compounds containing azoles as ligands with I-N bonds.[2,15,20] The azoles are an important class of heterocycles due to their unique pharmaceutical and explosive properties. Particularly, tetrazoles are known for high enthalpy of formation,[25,26] which makes them highly effective propellants[26] and explosives producing only molecular nitrogen as waste. Many groups have demonstrated the transfer of tetrazoles to various substrates via Suarez reactions[27] or HV iodine(III) mediated (tetra)azole transfer.[8,28] In this context, synthesis of HV iodine(III) compounds containing transferable tetrazoles which are both stable and reactive would be highly desirable.

5.1.2. Tetrazoles and their properties

Tetrazoles are unsaturated five-membered heterocycles with four nitrogen atoms in the ring. The enthalpies of energetic chemical systems are governed by their molecular structure. From imidazole ($\Delta H_f^o = + 58.5$ kJmol^{-1}) to 1,2,4-triazole ($\Delta H_f^o = + 109.0$ kJmol^{-1}) to tetrazole ($\Delta H_f^o = + 237.2$ kJmol^{-1}),[32] the heats of formation get increasingly positive. Since the generation of molecular nitrogen as an end-product of propulsion or explosion is highly desired to avoid environmental pollution and health risks,as well as to reduce detectible plume signatures, compounds containing a backbone of directly linked nitrogen atoms (catenated nitrogen) are of great interest. The high nitrogen content of tetrazole and its derivatives has led to investigations for their use as potential energetic materials. Tetrazoles[1-6] are of interest, due to properties such as complex-formation ability, biological activity, and especially their highly positive enthalpy of formation,[7] which makes them attractive as effective propellants and explosives producing molecular nitrogen as the dominating gaseous product of decomposition. C-(5-)substituted tetrazoles RCN$_4$H resemble structurally carboxylic acids RCO$_2$H and are often characterized by similar (typically, within an order of magnitude) values of K$_a$,[8] which is why they are often referred to as tetrazolic acids. For instance, pK$_a$ of 5-methyltetrazole CH$_3$CN$_4$H is around 5.6,[8] while pK$_a$ of CH$_3$CO$_2$H is 4.8.[9] Likewise, the pK$_a$ values of 5-phenyltetrazole and benzoic acid are respectively 4.8[8] and 4.2.[9] It was therefore to be expected that tetrazoles or tetrazolate anions can be used in the place of carboxylic acids or carboxylate anions to prepare the compounds ArI(N$_4$CR)$_2$ or cyclic iodanes where the tetrazole is connected to phenyl ring, analogue of 2-iodobenzoic acid. In addition, we can also synthesize N-heterocyclic iodanes where tetrazole is a part of heterocycle and has I-N bonds as the hypervalen bond. Herein, we report the formation, isolation, structural characterization, and reactivity studies of acyclic compounds of the type

ArI(N$_4$CR)$_2$, as well as derived from 5-methyl-, 5-phenyl-, and 5-(p-tolyl)tetrazole. Along with this we also report the synthesis of N-heterocyclic iodanes containing tetrazole in the heterocycle.

5.2.   Results and discussion

5.2.1.   Synthesis of acyclic HV iodine(III) compound containing tetrazole ligands with I-N bonds.

The reactions between PhIO and trimethylsilyl halides TMSX, hydrogen halides or carboxylic acids are convenient routes to synthesize various HV iodine(III) compounds such as PhIF$_2$,[29–31] PhI(N$_3$)$_2$,[32,33] PhI(NCO)$_2$,[33] PhI(OAc)$_2$,[29,34] PhI(OCOCF$_3$)$_2$,[32,35] etc. In our initial efforts, PhIO was reacted with 2 equivalents of **1a** to afford compound **2** in high yield (**Table 5-1**, Entry 1-3) in various solvents such as DCM, CHCl$_3$, and CH$_3$CN. The HV iodine(III) compound **2** was characterized by ^{1}H and ^{13}C NMR, and MALDI-Tof . The compound **3a** was isolated as an oily substance and it turned into a sticky solid upon drying under high vacuum which is stable at low temepratures for several weeks. After the ^{1}H NMR and MALDI-Tof data analysis, it was revealed that **3a** exists as symmetric HV iodine(III) compound. After synthesizing compound **3a** in high yields from PhIO, our next efforts were focused on the synthesis of HV iodine(III) compounds containing different tetrazoles such as 5-phenyl tetrazole (**1b**) and 5-tolyl tetrazole (**1c**).
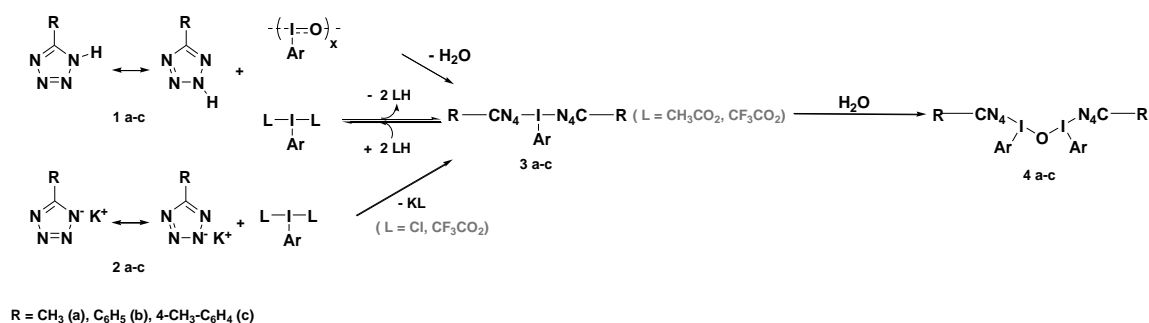
Scheme 5-1. Synthetic routes to prepare different HV iodine(III) compounds containing different tetrazoles.

Table 5-1. Synthesis of HV iodine(III) compounds containing various tetrazoles in different solvents at 25 °C

Entry	HV iodine(III) precursors	HN_4CR, R =	Solvent	Time	Yield (%)
1	PhIO (2 equiv.)	CH_3 (2 eq.)	CH_3CN	30 min	70
2			DCM		85
3			$CHCl_3$		82
4	$PhI(OAC)_2$ (1 equiv.)	CH_3 (2 eq.)	CH_3CN	30 min	12
5	$PhI(OCOCF_3)_2$ (1 equiv.)				25

The products from the reactions of PhIO and compounds **1b** and **1c** (2 equiv. vs. PhIO) were precipitated out as off-white solids in 2 h that were found to be insoluble in any solvent except MeOH. It is known that the reaction between PhIO and nucleophiles such as AcOH and CF_3COOH usually generates oligomeric HV iodine(III) compounds[34]. In the similar way it could be suspected that the compounds obtained from the reactions of PhIO and **1b** or **1c** were to be oligomeric HV iodine(III) compounds **3** or **4** respectively. We have concluded that unlike **3** and **4**, compound **2** from the reaction of PhIO and **1a**, was formed in high yields as soluble symmetric HV iodine(III) species. The reason could be attributed to the solubility of the compound **2** and **1a** which becomes the driving force for the reaction to proceed to completion. On the other hand, the oligomeric HV iodine(III) compounds **3** and **4**, from the reaction of PhIO and **1b** or **1c**, were

insoluble in CH$_3$CN hence there was no driving force for the reaction to reach completion. The contact time of PhIO (1 eq.) and **1b** or **1c** (2 eq.) in CH$_3$CN was increased to 20 h. The increased time of contact resulted in off-white solids in both the cases and both products were found soluble in polar solvents such as DMF. The ^{1}H NMR analysis of both off-white solid products in DMF-d$_7$ revealed them to exist as μ-oxo products.

Our efforts were now focused on exploring other methods to prepare symmetric HV iodine(III) compounds containing **1b** and **1c** were explored to eliminate the necessity of excess amount of tetrazole. To achieve this goal ligand exchange reactions of HV iodine(III) precursors such as PhI(OAc)$_2$ with **1a** were used (**Scheme 5-2**). Varvoglis and coworkers have shown that various acidic N-containing ligands can participate in exchange reactions with HV iodine(III) compounds such as PhI(OAc)$_2$.[1,2] The reaction of PhI(OAc)$_2$ with **1a** afforded **3a** in 12 % yield (**Table 5-1**, Entry 4). Furthermore, the yield remained similar even when the reaction time was increased. The lower yield might be a consequence of low affinity of **1a** for HV iodine(III) center than acetoxy groups or low nucleophilicity of compound **1a** to replace acetoxy groups of PhI(OAc)$_2$ or low stoichiometric ratio of **1a** to replace all the acetoxy groups of PhI(OAc)$_2$. This encouraged us to perform a solution study by ^{1}H NMR in order to investigate the ability of **1a** to replace the acetoxy groups of PhI(OAc)$_2$.
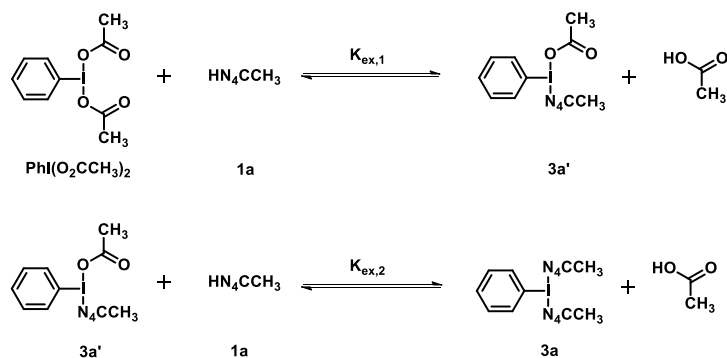
Scheme 5-2. Synthesis of bis(5-methyltetrazolyl)iodobenzene from PhI(OAc)$_2$.

The exchange of the acetoxy groups in PhI(OAc)$_2$ with **1a** at the HV Iodine(III) center was studied by ^{1}H NMR in CD$_3$CN. The PhI(OAc)$_2$ (10 mM in CD$_3$CN) was mixed with different amounts of **1a** (1, 2, and 4 equivalents vs. PhI(OAc)$_2$. When 1 eq. of **1a** vs. PhI(OAc)$_2$ was mixed in CD$_3$CN afforded **3a** in 17% (the ^{1}H NMR yields were calculated using equation 1) and asymmetric compound **3a'** in 10 % ^{1}H NMR yield as calculate after the equilibrium had established (ca. 5 h). When the 2 eq. of **1a** (vs. PhI(OAc)$_2$ was mixed with PhI(OAC)$_2$ the ^{1}H NMR yield of compound **2** was 18% and the ^{1}H NMR yield of the asymmetric compound **3a'** was similar. When 4 eq. of **1a** was mixed with PhI(OAc)$_2$, the amount of **3a** and **3a'** remained constant. Another set of experiments were carried (**Figure 5-1b**) where the isolated compound **3a**, from the reaction of PhIO and **1a**, was mixed with different amounts of AcOH in CD$_3$CN (1, 2, and 4 equivalents related to compound **3a**). When 1 eq. of AcOH related to **3a** was added the formation of PhI(OAc)$_2$ and mixed compound **3a'** was immediately evident with NMR yields of 33% and 9.5% respectively (calculated after the equilibrium had been established i.e. at 5 h). When 2 eq. of AcOH was mixed with the solution of **3a** , the ^{1}H NMR yields for PhI(OAc)$_2$ and the compound **3a'** were calculated to be 85.5% and 29% respectively. And the 4 eq. of AcOH related to **2** was sufficient enough to replace all the tetrazole from the di- and mixed compounds to give PhI(OAc)$_2$ as the

only product (**Figure 5-1b**). These ^{1}H NMR solution studies suggested that the acetoxy groups have more affinity towards HV Iodine(III) center than the tetrazolyl group in CD$_3$CN.
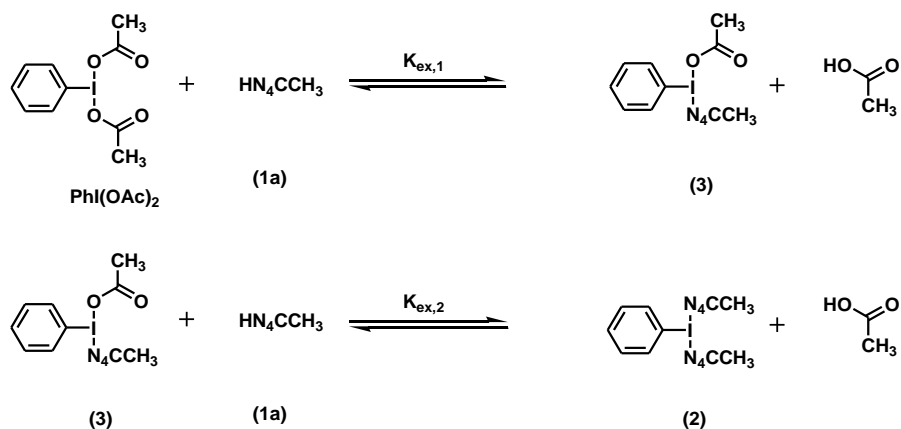
Scheme 5-3. Exchange of the acetoxy groups in PhI(OAc)$_2$ with **1a**.
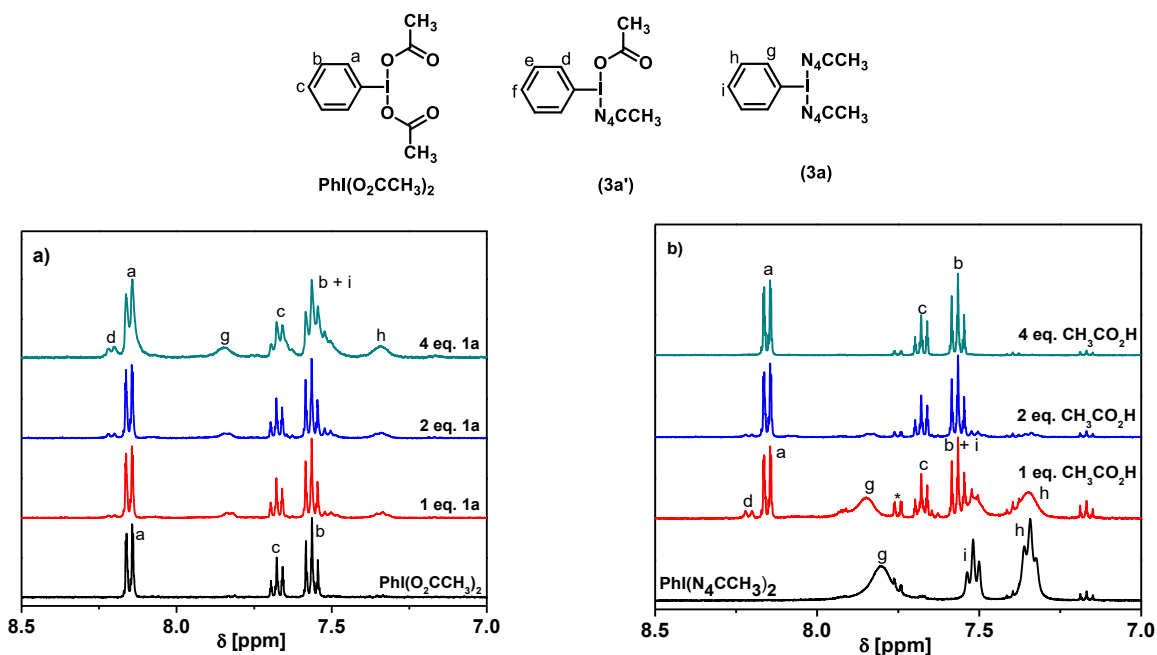
Figure 5-1. Spectra of equilibrated (5 h) reaction mixtures containing PhI(OAc)$_2$ (10 mM) and series of CH$_3$CN$_4$H (a) and (b) compound 2 (10 mM) and series of AcOH in CD$_3$CN.

The solution study demonstrated that the exchange between acetoxy group of PhI(OAc)$_2$ and **1a** is not an efficient way to synthesize compound **3a**. Even the high concentration of compound **1a** was incapable of replacing all the acetoxy groups of PhI(OAc)$_2$. The quest to achieve the symmetric HV Iodine(III) species containing tetrazoles with minimum amount used persisted. We moved to the synthesis of symmetric HV Iodine(III) species containing tetrazoles with I-N bonds by the exchange reaction of more nucleophilic potassium salt of **1a**, **1b**, and **1c** and HV Iodine(III) precursors such as PhICl$_2$ and PhI(OCOCF$_3$)$_2$.

It is a well-known practice to synthesize symmetric HV Iodine(III) compounds by reaction a HV Iodine(III) precursor and a sodium or potassium salts of nucleophile.[17–19,33] First, PhICl$_2$ was prepared by reacting PhI with sulfuryl chloride in AcOH. The isolated crystalline PhICl$_2$ was then reacted with the potassium salts **2a**, **2b**, and **2c** (2 equiv. vs. PhICl$_2$) in dry CH$_3$CN (Scheme 4) for 15 h affording symmetric HV Iodine(III) compounds **3a-c** in 82%, 65%, and 69% (**Table 5-2**, Entry 1-3) yields respectively. The isolated yields were encouraging and suggested that the efficiency of ligand exchange reactions was increased with the increase in nucleophilicity of tetrazoles to produce the desired symmetric HV Iodine(III) compounds with I-N bonds. Compounds **3a-c** were analyzed with ^{1}H and ^{13}C NMR, and MALDI-Tof. When the same reactions were carried out in normal CH$_3$CN, the compounds **2a** gave the same product **3a** in similar yields. But when PhICl$_2$ was reacted with **2b** or **3c** in regular CH$_3$CN, the resulted products were μ-oxo-bridged HV Iodine(III) compounds **4b** and **4c** as evident from ^{1}H NMR, as shown in **Scheme 5-1**. The similar exchange reactions were carried out with PhI(OCOCF$_3$)$_2$ and potassium salts **2a**, **2b** and **2c**, in dry CH$_3$CN for 15 h. The isolated yields of **3b** and **3c** were found to be higher compared to when synthesized from PhICl$_2$ due to the solubility of the byproduct potassium trifluoroacetate and the precipitation of the products in CH$_3$CN. In the case of PhICl$_2$, the byproduct KCl has a
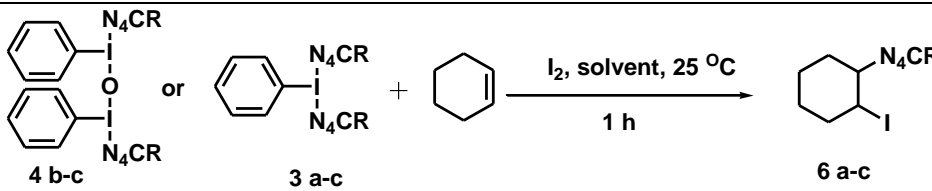
limited solubility in CH$_3$CN and hence also precipitates out with the products **3b** and **3c**. As result, loss of products become inevitable duo to extra purification steps to remove KCl. This precipitation of KCl was a driving force in the case of the reaction of PhICl$_2$ and **2a** that afforded higher yield than the reaction of PhI(OCOCF$_3$)$_2$ and **2a** (**Table 5-2**, Entry 1 and 4). These methods turned out to be the most efficient methods to prepare symmetric HV Iodine(III) compounds **3a-c** containing tetrazoles with minimum equivalents of tetrazole used.

Table 5-2. Synthesis of (RCN$_4$)$_2$IPh compounds under different conditions and synthetic routes at 25 °C in CH$_3$CN

Entry	HV Iodine(III) precursor	K$^+$N$_4$CR, R =	Yields (%)
1	DCIB	CH$_3$	82
2		p-Tol	65
3		Ph	69
4	PhI(OCOCF$_3$)$_2$	CH$_3$	72
5		p-Tol	65
6		Ph	70

5.2.2. Reactivity

Suarez and coworkers[40,41] demonstrated the use of PhI(OAc)$_2$-I$_2$ in the oxidative addition of acetoxy groups to the various N-based substrates. The reaction was further implemented to iodoacyloxylation of various olefins.[27] In this context, the compounds **3a-c** were reacted with cyclohexene in the presence of I$_2$ in different solvents to iodotetrazolylation of styrene and cyclohexene. All the reactions were performed in dark at 25 ^{0}C for 1 h as shown in **Table 5-3**.

Table 5-3. Iodotetrazolylation reaction of cyclohexene in different solvents.

Entry	R in PhI(N$_4$CR)$_2$	Solvent	Yield (%)
1	CH$_3$	CH$_3$CN	75
2	,,	DCM	70
3	,,	CHCl$_3$	69
4	,,	DMF	80
5	,,	MeOH	82
6	4-CH$_3$C$_6$H$_4$	CH$_3$CN	80
7	,,	DCM	75
8	,,	MeOH	89[a]
9	C$_6$H$_5$	CH$_3$CN	85
10	,,	DCM	82
11	,,	MeOH	90[a]
12	μ-oxo 4-CH$_3$C$_6$H$_4$	DCM	72
13	μ-oxo C$_6$H$_5$	DCM	82

[a] the reaction proceeded through the formation of iodomethoxylation reaction.

A plausible mechanism was proposed below that shows the formation of an intermediate forming iodo-tetrazole adduct and which in turn reacts with olefin for yield the desired products. When the reactions with compounds **3b** and **3c** with cyclohexene were conducted in methanol (Table 3, entries 8 and 11), the product obtained in both cases was compound **7** (**Scheme 5-4**). This product could be the result of an exchange reaction between **3b** or **3c** and methanol (yielding PhI(OCH$_3$)$_2$), followed by reaction of the newly formed compound with iodine and eventually – with cyclohexene.
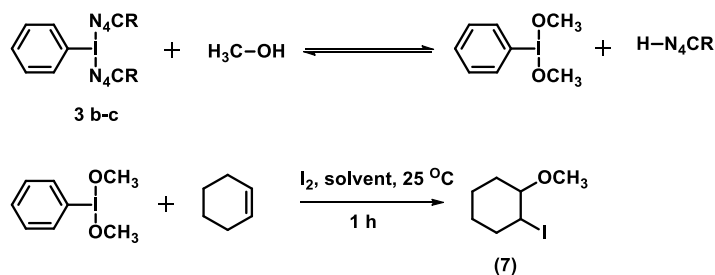
Scheme 5-4. The exchange reaction of compounds **7** and **8** with MeOH and further reaction with cyclohexene in the presence of I_2.

This reaction was extended to styrene and under the similar conditions two isomers **a** and **b** were obtained. The product **a** was always in higher yields than the product **b** in all given conditions and synthetic routes as shown in **Table 5-4**. It was already reported and explained[27] that the intermediate carbocation is more substituted and hence more favorable which results in higher yield of compound **a**.

Table 5-4. Iodotetrazolylation reaction of styrene in different solvents
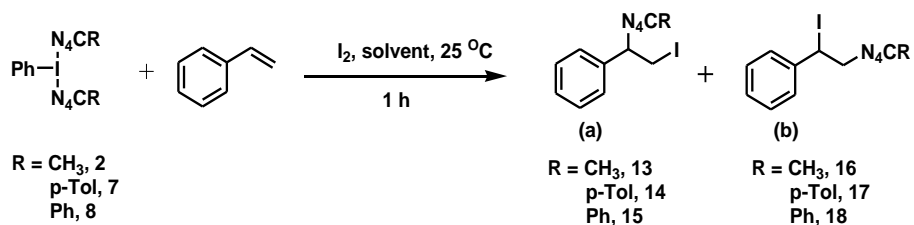
Entry	PhI(HN₄CR)₂, R =	Solvent	Yields (%)	
			(a)	(b)
1	CH₃	CH₃CN	75	20
2		DCM	70	15
3		MeOH	82	10
4	p-Tol	DCM	80	12
5	Ph	DCM	85	16
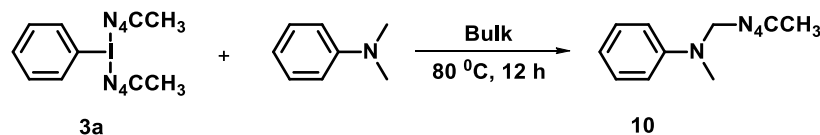
Scheme 5-5. Oxidative radical tetrazolylation of N,N-dimethylaniline at 80 °C in CH$_3$CN.

Proposed Mechanism
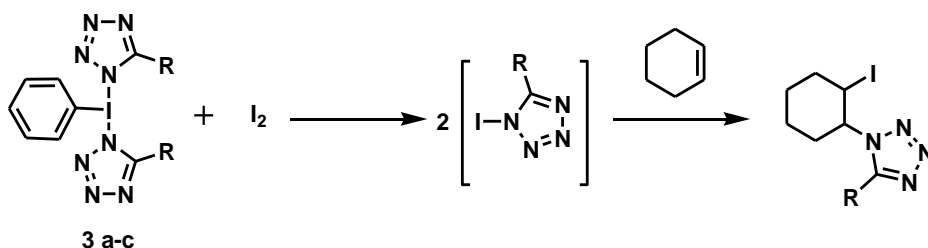
In addition to these PhI(N$_4$CR)$_2$-I$_2$-mediated reactions, the possibility of radical reactions of compound **3a** in the absence of I$_2$ was explored. The reaction between **3a** and *N,N*-dimethylaniline (Scheme 4) was performed at 80 °C in bulk for 12 h and the product **10** was isolated using preparative TLC.

5.3.   Synthesis of I-sunstituted benzoiodazolotetrazoles

As shown above, that tetrazoles are analogoues of the carboxylate and they can form HV I-N bonds. Based on this observation, our next steps were to synthesize an analogue of 2-iodobenzoic acid where the carboxylate is replaced with terazole (**Scheme 5-6**) to form 5-(2-iodo-phenyl)-1H-tetrazole and upon oxidize possibly forms a HV iodine(III) compound with I-N bond.

5.3.1. Synthesis of 5-(2-iodo-phenyl)-1H-tetrazole

In our initial step, the 5-(2-iodo-phenyl)-1H-tetrazole was synthesized using a literature procedure but with modification. 2-iodobenzonitrile (1 eq) was reacted with NaN_3 (2.0 eq) and NH_4Cl (2.0 eq) in DMF (50.0 mL) under reflux condition for 20 h. The reaction was cooled down at room temperature and deionised water (50.0 mL) was added (dissolves unreacted NaN_3, NH_4Cl, and the sodium salt of product) followed by the dropwise addition of concentrated HCl untill no precpitation was formed. The precipitated was seperated by vacuum filtaration and washed with a large amount of water. The obtained crude precipitate was dissolved in a solution of NaOH (20 %, w/v) followed by filteration. The clear basic solution was again acidified by dropwise addition of concentrated HCl. The obtained product was isolated in high yields and characterized by ^{1}H and ^{13}C NMR spectroscopy.
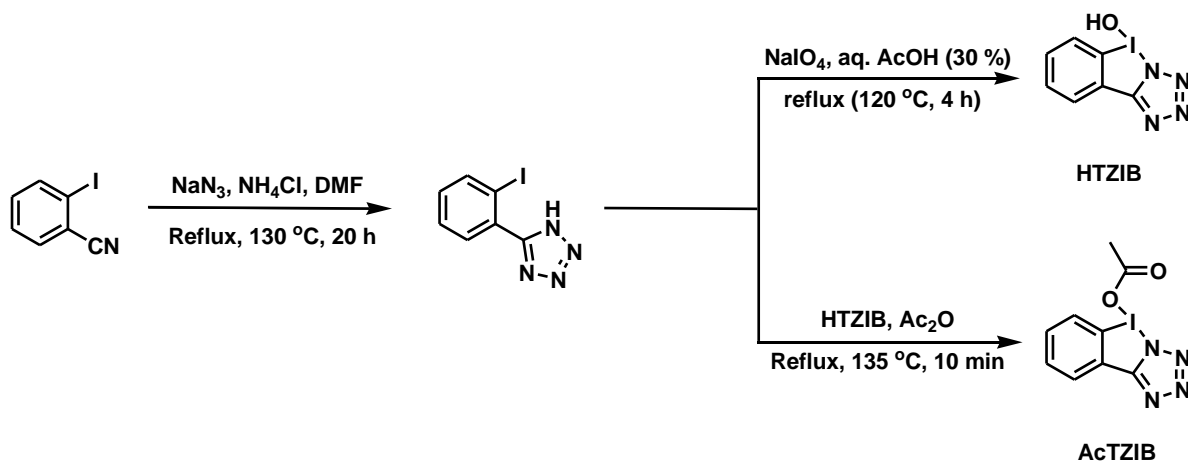
Scheme 5-6. Synthesis of HTZIB and AcTZIB.

5.3.2. Synthesis and characterization of HTZIB

After isolation, the compound was oxidized with NaIO$_4$ in aq. AcOH (30 %, v/v) under refluxed conditions and after 4 h (**Scheme 5-6**), while cooling down brown crystals formed. The crystals were washed with large amounts of diethyl ether, to remove the staarting material, and were analyzed by ^{1}H and ^{13}C NMR spectroscopy single crystal X-ray crystallography (**Figure 5-2**) and found to be a HV iodine(III) compound, HTZIB, with O-I-N bond as shown in **Scheme 5-6**. The bond distance between I-N (end-tetrazole) was found to be 2.369 Å and whereas, O-I bond distance was 1.969 Å (**Table 5-5**). HTZIB was found to be explosive in nature due to the N-atom of terazole is directly bounded to HV iodine(III) which makes the compound very unstable. The cause of the explosion is unknown but the speculations are either the vicinty of metal spatula, tapping or static shock.
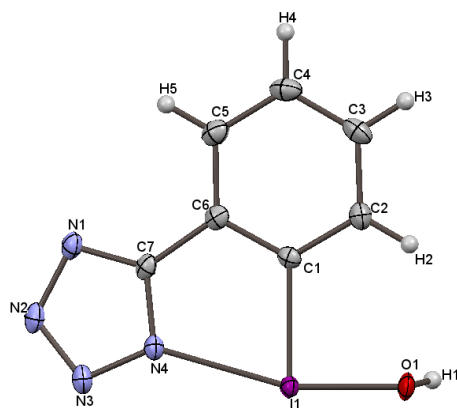
Figure 5-2. X-ray crystal structure of HTZIB (50 % probability)

Table 5-5. Selected bond distances and angles of HTZIB determined by the X-ray crystallography

Selected bond distances (Å)		Selected angles	
I1-O1	1.969	O1-I1-C1	89.62
I1-N4	2.369	N4-I1-C1	74.54
I1-C1	2.126	N4-I1-O1	164.16
		I1-N4-C7	111.86

5.3.3. Synthesis and characterization of AcTZIB

When HTZIB was refluxed with acetic anhydride, the obtained white crystalline solid was anaylzed by ^{1}H and ^{13}C NMR spectroscopy single crystal X-ray crystallography (**Figure 5-3**). The bond distances between I-N was measured to be 2.198 Å and the distance between O-I is 2.147.
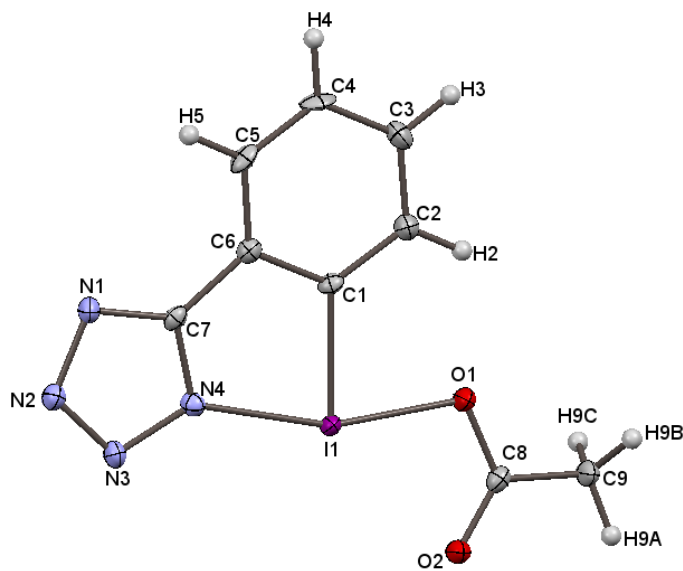
Figure 5-3. X-ray crystal structure of AcTZIB (50 % probability).

Table 5-6. Selected bond distances and angles of AcTZIB determined by the X-ray crystallography.

Selected bond distances (Å)		Selected angles	
I1-O1	2.139	O1-I1-C1	85.57
I1-N4	2.202	N4-I1-C1	76.72
I1-C1	2.121	N4-I1-O1	161.93
I1-O2	2.791	I1-N4-C7	114.53

5.4. Conclusions

In conclusion, novel symmetric HV iodine(III) reagents containing different 5-substituted tetrazoles were prepared and were found to be reasonably stable under ambient conditions in both the solid and solution states. The compounds proved to be strong oxidants. An oligomer with I-O-

based backbone and tetrazole end groups was characterized by X-ray diffraction. The use of these reagents allowed oxidative iodotetrazolylation reactions of styrene and cyclohexene as well as radical transfer of tetrazole groups to *N,N*-dimethylaniline. Further investigations focused on expanding the utility of the HV iodine(III) reagents is currently in progress. In another part we could demonstrate that when carboxylate in 2-iodobenzoic acid is replaced with tetrazole it behaves in the similar manner as carboxylate and when oxidized it forms a new class of HV iodine(III) with I-N bond. Two different HV iodine(III) were synthesized, HTZIB and AcTZIB and shown to have HV bonds.

5.5. Experimental section

5.5.1. Materials

5-Methyl-1H-tetrazole (Alfa Aesar, 97 %), 5-phenyl-1H-tetrazole (Alfa Aesar, 99 %), 5-(p-tolyl)-1H-tetrazole (TCI, 98 %), (diacetoxyiodo)benzene (PhI(O$_2$CCH$_3$)$_2$, Acros, 98 %), [bis(trifluoroacetoxy)iodo]benzene (PhI(O$_2$CCF$_3$)$_2$, Acros, 98 %), cyclohexene (Sigma-Aldrich, 97+ %), styrene (Acros, 99 %), trans-2-[3-(4-tert-butylphenyl)-2-methyl-2-propenylidene]malononitrile (DCTB, TCI, 98 %), NaCl (Sigma-Aldrich, 99.9 %), NaNO$_3$ (Sigma-Aldrich, 99.9 %), (*n*-Bu)$_4$NPF$_6$ (TCI, 98 %), I$_2$ (Sigma-Aldrich, 99.8 %), Na$_2$S$_2$O$_3$ (Acros, 99.8 %), CH$_3$CO$_2$H (Sigma-Aldrich, 99 %), Na$_2$SO$_4$ (Sigma-Aldrich, 99.8 %), *N,N*-dimethylaniline (Sigma-Aldrich, 99 %) were used as received. Iodosylbenzene (PhIO) was synthesized using a procedure described in the literature,[10] which is based on the hydrolysis of PhI(O$_2$CCH$_3$)$_2$ with 3 M aqueous NaOH (pellets, 97+ %, Sigma-Aldrich, were employed to prepare the solution), followed by washing with chloroform (Acros, 99 % extra pure). Dichloroiodobenzene (PhICl$_2$) was synthesized using a procedure described in the literature.[11] The solvents, including anhydrous

acetonitrile (Acros, 99.9 %), anhydrous dichloromethane (Acros, 99.9 %), 1,2-dichloroethane (Acros, 99.8 %), diethyl ether (Acros, 99 %), *n*-hexane (Acros, 99.9 %), methanol (Acros, 99.8 %) were used as received.. The deuterated solvents, DMSO-*d₆* (Acros, 99.8 % D), DMF-*d₇* (Alfa Aesar, 99.5 % D), CD₃CN (Cambridge Isotope Laboratories, 99.8 % D), CDCl₃ (Cambridge Isotope Laboratories, 99.8 % D), and CD₃OD (Cambridge Isotope Laboratories, 99.8 % D), contained a small amount of tetramethylsilane (TMS) as a chemical shift reference. All chemicals were used as recieved without further purification.

5.5.2.   Analytical procedures

NMR spectra were recorded on a Bruker Avance DRX (400 MHz) spectrometer. Compound **3b-c** and **4b-c** were characterized by MALDI-ToF. MALDI mass spectra were aquired on a Shimadzu Axima Performance MALDI TOF-TOF (Shimadzu Biotech) in both positive and negative ion reflectron modes (100-1000 Da). For each compound, 100 profiles of 10 spectra/profile were collected at repetition rates of either 10 or 50 Hz. Laser power was optimized for each sample based on the intensity and resolution of the peaks in the spectra. Pulsed ion extraction voltages were optimized for the expected molecular weight of each compound. The matrix used was DCTB dissolved in methanol (30 mg/mL) and NaCl and NaNO₃ were used as doping agents. All spectra were baseline subtracted and Gaussian filtered for final analysis and compared with the matrix spectrum. The exact mass for compounds **3a, 6a-c, 8a-c, 9a-c**, and **10** was obtained using Shimadzu LCMS-IT-ToF. Standard conditions (electrospray ion source, positive-ion acquisition mode, interface voltage of +4.50 kV, CDL temperature of 200 °C, and block heater temperature of 200 °C) were used to identify all compounds except **3a**. Due to the instability of **3a**, a small peak corresponding to a fragment could only be observed when the

analysis conditions were changed as follows: electrospray ion source, positive-ion acquisition mode, interface voltage of +1.00 kV, CDL temperature of 100 °C, and block heater temperature of 100°C. However, the HRMS data for **4b** and **3c** could not be obtained due to fragmentation of the fragile hypervalent I-N bonds. Electrochemical measurements were carried out in an electrochemical cell system controlled with a CHI620E electrochemical station (CH Instruments, Inc., USA) with a Pt wire as the counter electrode, $AgNO_3/Ag$ as the reference and glassy carbon (GC) as working electrode while purging dry argon. All potential values are referenced to $AgNO_3/Ag$ in 0.1 M (n-Bu)$_4$NPF$_6$ with 0.01 M $AgNO_3$ in DMF. Samples were prepared by dissolving 10^{-5} mol of the studied HV iodine(III) compounds in 10 mL of 0.1 M solution of (n-Bu)$_4$NPF$_6$ in dry and deoxygenated DMF. The sample (10 mL) was divided in 3 parts and CV measurements were done on each part only once at a particular scan rate. For comparison, first, the redox potential of 1 mM ferrocene solution in DMF was measured with respect to $AgNO_3/Ag$ at the same scan rates. All samples were prepared in glove box to avoid moisture or air. X-ray diffraction setup is described in the SI.

5.5.3. General procedure for the synthesis of HV iodine (III) compounds 3a, 4b, 4c, 5b, and 5c

In a 10 mL dry reaction tube, a magnetic stir bar was placed followed by PhIO (2.0 mmol, 1 eq.) and **1a** (4.0 mmol, 2 eq.). The tube was capped with a rubber septum and wrapped with aluminum foil to prevent exposure of the contents to light. Then, dry solvent (2.0 mL) was injected, the tube was immersed in a water bath at 25 °C, and the mixture was stirred until a clear solution was formed (ca. 30 min). The solvent was then evaporated under reduced pressure and the desired product was isolated. Similar experiments were performed in CH$_3$CN using tetrazoles **1b** and **1c**

for two different time intervals: 2 h and 20 h. When the reaction time between PhIO and **1b** or **1c** was 2 h, the products were **5b** or **5c**, whereas, when contact time was increased to 20 h, mixture of oligomers **4b** or **4c** were obtained. Due to the poor solubility of both **5b** and **5c**, the spectroscopic characterizations were not performed.

Bis(5-methyltetrazolyl)iodobenzene (3a). Following the general procedure, PhIO (0.44 g, 2.0 mmol) and 1a (0.34 g, 4.0 mmol) were added in a vial followed by the addition of anhydrous CH_2Cl_2 (2.0 mL) and then removal of CH_2Cl_2 in 30 min yielded 3a (0.63 g, 85 %) as a sticky solid; ^{1}H NMR (400 MHz, CD_3CN): δ 2.43 (s, 6H), 7.28 (t, J = 7.9 Hz, 2H), 7.46 (t, J = 7.5 Hz, 1H), 7.86 (d, J = 7.9 Hz, 2H); ^{13}C{^{1}H}NMR (100.578 MHz, CD_3CN): δ 9.3, 125.9, 132.0, 132.8, 134.4, 154.9 ppm; HRMS: calculated m/z for $C_8H_8IN_4^+$ [M-CH$_3$CN$_4$]$^+$: 286.9788; found: 286.9756; MALDI-ToF: calculated m/z for $C_{10}H_{11}IN_8Na^+$ [M+Na]$^+$: 393.0038; found: 392.9162.

μ-Oxo-bis(5-phenyltetrazolyl)iodobenzene (4b). Following the general procedure, PhIO (0.44 g, 2.0 mmol) and 1b (0.58 g, 4.0 mmol) were added in a vial followed by the addition of anhydrous CH_3CN (20.0 mL) and then removal of solvent in 20 h yielded 4b (0.80 g, 60 %) as an off-white solid; ^{1}H NMR (400 MHz, DMF-d_7): δ 8.00 (s, 8H), 7.47 (dd, J = 36.0, 29.6 Hz, 12H).; ^{13}C{^{1}H}NMR (100.578 MHz, DMF-d_7): δ 126.6, 127.0, 128.0, 130.0, 131.0, 131.1, 133.7, 137.7 ppm; MALDI-ToF: calculated m/z for $C_{19}H_{15}I_2N_4O^+$ [M-N$_4$CC$_6$H$_5$]$^+$: 568.9335; found: 568.8090.

μ-Oxo-bis(5-p-tolyltetrazolyl)iodobenzene (4c). Following the general procedure, PhIO (0.44 g, 2.0 mmol) and 1c (0.64 g, 4.0 mmol) were added in a vial followed by the addition of anhydrous CH_3CN (20.0 mL) and then removal of solvent in 20 h yielded 4c (0.83 g, 56 %) as an off-white solid; ^{1}H NMR (400 MHz, DMF-d_7): δ 2.35 (s, 6H), 7.31 (d, J = 7.75 Hz, 4H), 7.44 (t, J = 7.5 Hz, 4H), 7.55 (t, J = 7.9 Hz, 2H), 7.92 (d, J = 7.8 Hz, 4H), 8.03 (b, 4H); ^{13}C{^{1}H}NMR

(100.578 MHz, DMF-d_7): δ 140.30, 137.68, 133.80, 132.06, 131.22, 130.78, 130.60, 129.74, 127.99, 126.97, 126.66, 20.80 ppm; MALDI-ToF: calculated m/z for $C_{28}H_{23}I_2N_8O^-$ [M-H]$^-$: 741.0084; found: 740.9355.

5.5.4. General procedure for the synthesis of PhI(N$_4$CR)$_2$ (R = CH$_3$, C$_6$H$_5$, and 4-CH$_3$C$_6$H$_4$)

In a 10 mL dry reaction vial, a magnetic stir bar was placed followed by PhICl$_2$ (2.0 mmol) and **2a** (4.0 mmol). The tube was capped with a septum and wrapped with aluminum foil and then dry CH$_3$CN (4.0 mL) was injected. The tube was immersed in a water bath at 25 °C and the mixture was stirred for 15 h. The white precipitate (KCl) was filtered off and washed with CH$_3$CN (5×2 mL). The combined solvent was evaporated under reduced pressure to afford **3a** as yellow oil. The oil was dried under high vacuum for 15 h to obtain a sticky solid in 82 % yield. Similar experiments were performed with **2b** and **2c** (to afford **3b** and **3c**, respectively). In these cases, solids were isolated by filtration and washed with a minimum amount of water (2×2 mL) in order to remove the byproduct, KCl, followed by CH$_3$CN (5×10 mL) and finally with diethyl ether. The products were dried overnight under high vacuum to obtain the pure products with yields indicated in Table 2. The experiments with PhI(O$_2$CCF$_3$)$_2$ and **2a-c** were performed under similar conditions but with the change in the purification steps. After the reaction between PhI(O$_2$CCF$_3$)$_2$ and **2a**, the CH$_3$CN was evaporated and the obtained sticky yellow solid was dissolved in CH$_2$Cl$_2$. The CH$_2$Cl$_2$ dissolves the desired product **3a**, leaving behind the salt, KO$_2$CCF$_3$ which was then filtered and further washed with CH$_2$Cl$_2$ (4×4 mL). The combined solvent was evaporated under reduced pressure to afford **3a** as yellow oil. The oil was dried under high vacuum for 15 h to obtain a sticky

solid in 70 % yield. Similar experiments were performed with **2b** and **2c** (to afford **3b** and **3c**, respectively). In these cases, solids were isolated by filtration and washed with CH$_3$CN (5×5 mL) in order to remove the byproduct, KO$_2$CCF$_3$, followed by diethyl ether and dried under vacuum.

Bis(5-phenyltetrazolyl)iodobenzene (3b). PhICl$_2$ (0.55 g, 2.0 mmol) and 2b (0.74 g, 4.0 mmol) were added to a vial, followed by anhydrous CH$_3$CN (20.0 mL), and the general method yielded 3b (0.68 g, 69 %); ^{1}H NMR (400 MHz, DMSO-d_6): δ 8.06 (d, J = 6.6 Hz, 6H), 7.59 (d, J = 7.5 Hz, 9H); ^{13}C{^{1}H}NMR (100.578 MHz, DMSO-d_6): δ 158.1, 134.1, 132.1, 131.4, 130.8, 129.7, 127.1, 126.5 ppm; MALDI-ToF: calculated m/z for C$_{13}$H$_{10}$IN$_4$Cl [M-PhCN$_4$+Cl]$^-$: 383.9644; found: 383.9654

Bis(5-(4-tolyltetrazolyl))iodobenzene (3c). PhICl$_2$ (0.55 g, 2.0 mmol) and 2c (0.79 g, 4.0 mmol) were added to a vial, followed by anhydrous CH$_3$CN (20.0 mL), and the general method yielded **3c** (0.68 g, 65%); ^{1}H NMR (400 MHz, DMSO-d_6): δ 8.08 (d, J = 7.7 Hz, 2H), 7.92 (d, J = 8.1 Hz, 4H), 7.62 (t, J = 7.4 Hz, 1H), 7.51 (t, J = 7.7 Hz, 2H), 7.38 (d, J = 8.1 Hz, 4H), 2.39 (s, 6H); ^{13}C{^{1}H}NMR (100.578 MHz, DMSO-d_6): δ 158.0, 140.7, 134.0, 132.1, 131.3, 130.2, 127.1, 125.1–124.5, 123.6, 21.3 ppm; MALDI-ToF: calculated m/z for C$_{22}$H$_{20}$IN$_8$$^+$ [M+H]$^+$: 523.0856; found: 523.0084

5.5.5. ^{1}H NMR studies of exchange reaction between acetoxy groups of PhI(O$_2$CCH$_3$)$_2$ with 1a in CD$_3$CN

In a 10 mL glass tube, PhI(O$_2$CCH$_3$)$_2$ (9.6 mg, 3.0×10^{-5} mol, to reach final concentration of 10 mM) was added in CD$_3$CN (3 mL) followed by C$_2$H$_4$Cl$_2$ (internal standard; 10 μL) and **1a** (2.5 mg, 3.0×10^{-5} mol, to reach final concentration of 10 mM) and the mixture was stirred to dissolve the components. Then, 0.8 mL of this solution was taken in a dark NMR tube and spectra

(8 scans) were collected. The equilibrium was determined as the time, at which the ratio of the integrals of the $C_2H_4Cl_2$ protons and aromatic protons of $PhI(O_2CCH_3)_2$ remained constant. It took 5 h to reach equilibrium. Similar experiments were performed where larger amounts of **1a** (2 and 4 eq.) in CD_3CN were used to replace acetoxy groups of $PhI(O_2CCH_3)_2$.

5.5.6.   Exchange of CH_3CN_4 groups in $PhI(N_4CCH_3)_2$ with acetoxy groups

In a 10 mL reaction tube, a stir bar was added followed by $PhI(N_4CCH_3)_2$ (11 mg, 3.0×10^{-5} mol; to reach final concentration of 10 mM) and the tube was wrapped with aluminum foil to protect the contents from light. CD_3CN (3.0 mL) was then added. The solution was stirred until it became homogeneous (30 min) at room temperature. Then, CH_3CO_2H (1.72 μL, 3.0×10^{-5} mol, to reach final concentration of 10 mM) was added followed by $C_2H_4Cl_2$ (10 μL, 0.13 mmol) and TMS vapors. Then, 0.8 mL of the solution were transferred into a dark (ambered) NMR tube and ^1H NMR spectra (8 scans) were collected. It took 5 h to reach equilibrium. Similar experiments were performed with larger amounts of CH_3CO_2H.

5.5.7.   Reaction of $PhI(N_4RC)_2$ and $RCN_4-I(Ph)-[O-I(Ph)]_n-N_4CR$ with cyclohexene in the presence of I_2

In a 10 mL reaction tube, a stir bar was placed followed by **3a** (0.37 g, 1.0 mmol) and the tube was wrapped with aluminum foil to protect the contents from light. Then, anhydrous CH_3CN (2.0 mL) was added and the tube was immersed in a water bath at 25 °C and stirred until the solution became clear (ca. 30 min). Then, I_2 (0.26 g, 1.0 mmol) was added and clear solution turned

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turbid white. This heterogeneous solution was stirred for another 5 min. and cyclohexene (0.11 mL, 1.0 mmol) was added using a micropipette. It was noted that upon the addition of cyclohexene the color turned brown and the solution remained heterogeneous. After 1 h, the reaction was quenched using 10 % $Na_2S_2O_3$ and the contents were extracted with CH_2Cl_2 (5×10 mL). All the CH_2Cl_2 layers were collected and washed with distilled water (3×10 mL), dried over Na_2SO_4, and then the solvent was evaporated using rotovap to obtain a yellow oil as the crude product. The crude product was dissolved in CH_2Cl_2 (1.0 mL) and hexane (20.0 mL) was added. Subsequently, the mixture was left at room temperature for about an hour to obtain crystals of pure **6a** (0.218 g, 74.8 % yield). Similar experiments were carried out with **3a** in different solvents and with **3b** and **3c** under the same conditions, as well as with **4b** and **4c** in DCM. In the later case, the products were identical to those isolated from the reactions involving **3b** and **3c**.

1-(2-iodocyclohexyl)-5-methyltetrazole (6a). Following the above procedure, product **6a** was obtained as colorless crystaline compound (0.22 g, 75 %); ^{1}H NMR (400 MHz, CDCl$_3$): δ 4.57 (ddd, J = 12.5,10.9, 4.3 Hz, 1H), 4.27 (td, J = 11.2, 4.2 Hz, 1H), 2.82–2.64 (m, 1H), 2.64 (s, 3H), 2.27–1.93 (m, 4H), 1.71 (dd, J = 7.1, 2.6 Hz, 1H), 1.68–1.41 (m, 2H); ^{13}C{^{1}H}NMR (100.578 MHz, CD$_3$CN): δ 152.7, 64.4, 40.4, 34.7, 33.9, 28.3, 25.1, 9.4 ppm; GC-MS: calculated m/z for $C_8H_{13}IN_4$: 292.12; found: 292.0. **6a** was reported by Hassner and co-workers but no NMR spectrum was reported.[12]

1-(2-iodocyclohexyl)-5-phenyltetrazole (6b). Following the above procedure, product 6b was obtained as colorless crystalline compound (0.30 g, 85 %); ^{1}H NMR (400 MHz, CD$_3$CN): δ 7.80–7.40 (m, 5H), 4.70 (ddd, J = 12.4, 10.9, 4.2 Hz, 1H), 4.64–4.50 (m, 1H), 2.64–2.55 (m, 1H), 2.39–2.04 (m, 4H), 1.75–1.12 (m, 3H); ^{13}C{^{1}H}NMR (100.578 MHz, CD$_3$CN): δ 155.6, 132.2,

130.3, 130.3, 125.1, 65.3, 40.2, 35.1, 33.9, 28.2, 25.0 ppm; GC-MS: calculated m/z for $C_{13}H_{15}IN_4$: 354.19; found: 354.0. ^{1}H NMR spectrum is in agreement with that reported for **6b**.[13]

*1-(2-iodocyclohexyl)-5-(p-tolyl)tetrazole (**6c**)*. Following the above procedure, product 6c was obtained as colorless crystalline compound (0.29 g, 80 %); ^{1}H NMR (400 MHz, CD$_3$CN + DMSO-d_6): δ 7.72 – 7.56 (m, 2H), 7.56 – 7.40 (m, 2H), 4.76 – 4.61 (m, 1H), 4.54 (td, J = 11.3, 4.1 Hz, 1H), 2.55 (ddd, J = 12.8, 5.6, 2.1 Hz, 1H), 2.46 (s, 3H), 2.29 (ddd, J = 6.0, 4.9, 3.1 Hz, 1H), 2.16 – 2.00 (m, 2H), 2.01 – 1.90 (m, 1H), 1.67 – 1.41 (m, 3H); ^{13}C{^{1}H}NMR (100.578 MHz, CD$_3$CN + DMSO-d_6): δ 141.37, 129.55, 128.78, 120.47, 117.24, 63.83, 33.69, 32.71, 26.82, 23.59, 20.25; HRMS: calculated for $C_{14}H_{17}IN_4$ [M+H]$^+$: 369.0566; found: 369.0571.

*1-iodo-2-methoxy-cyclohexane (**7**)*. ^{1}H NMR (500 MHz, CD$_3$CN): δ 4.06 (dd, J = 7.6, 5.5 Hz, 1H), 3.41 (s, 3H), 3.31 – 3.16 (m, 1H), 2.40 (d, J = 15.8 Hz, 1H), 2.21 (d, J = 3.3 Hz, 1H), 2.13 – 1.90 (m, 1H), 1.90 – 1.66 (m, 1H), 1.66 – 1.49 (m, 1H), 1.53 – 1.11 (m, 3H); GC-MS: calculated m/z for $C_7H_{13}IO$: 240.08; found: 240.00. The ^{1}H NMR spectrum is in agreement with that reported for **7**.[14]

5.5.8. Reaction of PhI(N$_4$CR)$_2$ with styrene in the presence of I$_2$

In a 10 mL reaction tube, a stir bar was added followed by **3a** (0.37 g, 1.0 mmol) and the tube was wrapped with aluminum foil. Anhydrous CH$_3$CN (2.0 mL) was added and the tube was immersed in a water bath at 25 °C and stirred until the solution became clear (ca. 30 min). Then, I$_2$ (0.26 g, 1.0 mmol) was added and clear solution turned turbid white. This heterogeneous solution was stirred for another 5 min and then styrene (0.12 mL, 1.0 mmol) was added using a

micropipette. After 1 h, the reaction was quenched using 10 % $Na_2S_2O_3$ and then the contents were extracted with CH_2Cl_2 (5×10 mL). All the CH_2Cl_2 layers were collected and washed with distilled water (3×10 mL), dried over Na_2SO_4, and the solvent was evaporated to afford a yellow oil as the crude product. The crude product (a mixture of isomers) was dissolved in CH_2Cl_2 (2.0 mL) and the isomers were separated using a preparative thin-layered chromatography. The separated isomers were dissolved in CH_2Cl_2 (1.0 mL) and hexane (20.0 mL) was added. Subsequently, the mixtures were left at room temperature for about an hour to obtain crystals of compounds **8a** and **8b** as the pure products. Similar experiments were carried out with **3a** in different solvents and with **3b** and **3c** under the same conditions.

*1-(2-iodo-1-phenylethyl)-5-phenyl-tetrazole (**8a**)*. Following the above procedure, product 8a was obtained as colorless crystalline compound (0.24 g, 75 %); ^{1}H NMR (400 MHz, CD_3CN): δ 7.44–7.37 (m, 5H), 6.20 (dd, J = 10.5, 4.7 Hz, 1H), 4.20 (t, J = 10.6 Hz, 1H), 3.94 (dd, J = 10.7, 4.8 Hz, 1H), 2.48 (d, J = 3.7 Hz, 3H); ^{13}C{^{1}H}NMR (100.578 MHz, CD_3CN): δ 164.1, 137.6, 130.3, 130.0, 129.9, 129.2, 128.7, 127.9, 126.9, 73.8, 69.9, 11.1 ppm; HRMS calculated for $C_{10}H_{11}IN_4$ [M+H]$^+$: 315.0095; found: 315.0101.

*1-(2-iodo-1-phenylethyl)-5-phenyl-tetrazole (**9a**)*. Following the above procedure, product 8a was obtained as colorless crystalline compound (0.24 g, 75 %); ^{1}H NMR (400 MHz, CD_3CN): δ 7.55–7.23 (m, 5H), 5.63 (dd, J = 10.5, 4.7 Hz, 1H), 4.19 (t, J = 10.6 Hz, 1H), 3.85 (dd, J = 10.7, 4.8 Hz, 1H), 2.54 (d, J = 3.7 Hz, 3H); ^{13}C{^{1}H}NMR (100.578 MHz, CD_3CN): δ 153.31, 137.4, 130.05, 129.14, 128.60, 127.95, 126.87, 73.73, 64.14, 6.57; HRMS calculated for $C_{10}H_{11}IN_4$ [M+H]$^+$: 315.0099; found: 315.0101.

*1-(2-iodo-2-phenylethyl)-5-phenyl-tetrazole (**8b**)*. Following the above procedure, product 8b was obtained as colorless crystalline compound (0.32 g, 85 %); ^{1}H NMR (400 MHz, CD$_3$CN): δ 8.14–8.12 (s, 2H), 7.55–7.54 (m, 5H), 7.54–7.41 (m, 3H), 6.31 (dd, J = 10.4, 5.3 Hz, 1H), 4.27 (t, J = 10.6 Hz, 1H), 2.16 (dd, J = 10.8, 5.3 Hz, 1H); ^{13}C{^{1}H}NMR (100.578 MHz, CD$_3$CN): δ 165.1, 136.6, 130.6, 129.5, 129.2, 129.1, 127.3, 127.1, 126.6, 69.5, 4.4; HRMS calculated for C$_{15}$H$_{13}$IN$_4$ [M+H]$^+$: 377.0261; found: 377.0258.

*1-(2-iodo-1-phenylethyl)-5-phenyl-tetrazole (**9b**)*. Following the above procedure, product 9b was obtained as white solid (60.2 mg, 16 %); ^{1}H NMR (400 MHz, CDCl$_3$): δ 7.69–7.50 (m, 5H), 7.48–7.36 (m, 5H), 5.62 (dd, J = 11.1, 4.4 Hz, 1H), 4.23 (t, J = 11.0 Hz, 1H), 3.77 (dd, J = 10.8, 4.4 Hz, 1H); ^{13}C{^{1}H}NMR (100.578 MHz, CDCl$_3$): δ 155.5, 136.7, 131.6, 129.8, 129.7, 129.4, 126.8, 123.8, 65.2, 6.1 ppm; HRMS calculated for C$_{15}$H$_{13}$IN$_4$ [M+H]$^+$: 377.0255; found: 377.0258.

*1-(2-iodo-2-phenylethyl)-5-tolyl-tetrazole (**8c**)*. Following the above procedure, product 8c was obtained as white solid (0.31 g, 80 %); ^{1}H NMR (400 MHz, CDCl$_3$): δ 8.15–7.99 (m, 2H), 7.53–7.42 (m, 2H), 7.41–7.32 (m, 3H), 7.28 (dd, J = 8.5, 0.6 Hz, 2H), 6.15 (dd, J = 10.3, 5.3 Hz, 1H), 4.31–4.13 (m, 1H), 3.87 (dd, J = 10.8, 5.3 Hz, 1H), 2.40 (s, 3H); ^{13}C{^{1}H}NMR (100.578 MHz, CDCl$_3$): δ 165.4, 140.6, 136.2, 129.6, 129.6, 129.2, 126.9, 126.9, 124.5, 70.0, 21.6 ppm; HRMS calculated for C$_{16}$H$_{15}$IN$_4$ [M+H]$^+$: 391.0414; found: 391.0414.

*1-(2-iodo-1-phenylethyl)-5-tolyl-tetrazole (**9c**)*. Following the above procedure, product 9c was obtained as white solid (50.0 mg, 12 %); ^{1}H NMR (400 MHz, CD$_3$CN): δ 7.36–7.29 (m, 9H), 5.73–5.69 (dt, J = 7.6, 3.8 Hz, 1H), 4.09 (td, J = 10.8, 6.6 Hz, 1H), 3.81 (dt, J = 20.8, 10.4 Hz, 1H), 2.33 (s, 3H); ^{13}C{^{1}H}NMR (100.578 MHz, CD$_3$CN): δ 156.3, 143.0, 137.7, 130.9, 130.6,

130.3, 130.2, 130.1, 130.0, 129.9, 127.9, 127.8, 127.5, 65.0, 21.5 ppm; HRMS calculated for $C_{16}H_{15}IN_4$ $[M+H]^+$: 391.0417; found: 391.0414.

5.5.9.   Reaction of PhI(N$_4$CCH$_3$)$_2$ with *N,N*-dimethylaniline in CH$_3$CN

In a 10 mL reaction tube, a stir bar was added followed by **3a** (5.84 g, 15.78 mmol) and the tube was wrapped with aluminum foil in order to protect the contents from light. The tube was carefully purged with nitrogent for 30 min and in a different vial, *N,N*-dimethylaniline (20 mL) was added and purged with nitrogen for 30 min. Then, *N,N*-dimethylaniline (10 mL, 78.9 mmol) was withdrawn using a nitrogen purged syringe and added to the tube containing **3a** immediately turning into a dark solution. The reaction tube was then immersed in an oil bath preheated to 80 °C and stirred there for 12 h. Then, the reaction was quenched using 10 % $Na_2S_2O_3$ (20 mL) and the contents were extracted with ethyl acetate (5×50 mL). All the ethyl acetate layers were collected and washed with distilled water (3×100 mL), dried over Na_2SO_4 and the solvent was evaporated to afford a dark brown oil as the crude product. The crude product was dissolved in ethyl acetate (10.0 mL) and the products were separated using a preparative thin-layered chromatography. The desired product was isolated as brown solid (0.17 g, 15%).

N-methyl-N-((5-methyl-1H-tetrazol-1-yl)methyl)aniline (**10**). Following the above procedure, product 10 was obtained in the mixture; ^{1}H NMR (400 MHz, CD$_3$CN): δ 7.14 (d, *J* = 8.8 Hz, 2H), 6.89-6.61 (m, 3H), 5.36 (s, 2H), 2.90 (s, 3H), 2.45 (s, 3H); ^{13}C{^{1}H}NMR (100.578 MHz, CD$_3$CN): δ 153.3, 137.4, 130.2, 130.0, 129.1, 127.9, 126.9, 73.7, 64.1; HRMS calculated for $C_{10}H_{13}N_5$ $[M+H]^+$: 204.1243; found: 204.1244.

5.6.   References

[1]   Hadjiarapoglou, A. L.; Spyroudis, S.; Varvoglis, *Synthesis (Stuttg).* **1983**, *1983*, 207–208.

[2]   Papadopoulou, A. M.; Varvoglis, *J. Chem. Res.* **1983**, *3*, 66–67.

[3]   V. V. Zhdankin, C. J. Kuehl, A. P. Krasutsky, M. S. Formaneck, J. T. Bolz, *Tetrahedron Lett.* **1994**, *35*, 9677–9680.

[4]   S. Akai, T. Okuno, M. Egi, T. Takada, H. Tohma, Y. Kita, *Heterocycles* **1996**, *42*, 47–51.

[5]   P. T. G. Rabet, G. Fumagalli, S. Boyd, M. F. Greaney, *Org. Lett.* **2016**, *18*, 1646–1649.

[6]   Y. V. Grigoriev, S. V. Voitekhovich, V. P. Karavai, O. A. Ivashkevich, *Chem. Heterocycl. Compd.* **2017**, *53*, 670–681.

[7]   Y. Fan, W. Wan, G. Ma, W. Gao, H. Jiang, S. Zhu, J. Hao, *Chem. Commun.* **2014**, *50*, 5733–5736.

8]   A. A. More, G. K. Pathe, K. N. Parida, S. Maksymenko, Y. B. Lipisa, A. M.

Szpilman, *J. Org. Chem.* **2018**, *83*, 2442–2447.

[9]   V. V. Zhdankin, R. M. Arbit, M. McSherry, B. Mismash, V. G. Young, *J. Am. Chem. Soc.* **1997**, *119*, 7408–7409.

[10]   V. V. Zhdankin, R. M. Arbit, B. J. Lynch, P. Kiprof, V. G. Young, *J. Org. Chem.* **1998**, *63*, 6590–6596.

[11]   M. M. Díaz-Requejo, T. R. Belderraín, M. C. Nicasio, S. Trofimenko, P. J. Pérez, *J. Am. Chem. Soc.* **2003**, *125*, 12078–12079.

[12]   J. W. W. Chang, P. W. H. Chan, *Angew. Chemie - Int. Ed.* **2008**, *47*, 1138–1140.

[13]   J. Llaveria, Á. Beltrán, M. M. Díaz-Requejo, P. J. Pérez, M. I. Matheu, S. Castillón, *Angew. Chemie - Int. Ed.* **2010**, *49*, 7092–7095.

[14]   B. V. Meprathu, J. D. Protasiewicz, *Tetrahedron* **2010**, *66*, 5768–5774.

[15]   A. Yoshimura, V. N. Nemykin, V. V. Zhdankin, *Chem. - A Eur. J.* **2011**, *17*, 10538–10541.

[16]   J. P. Brand, D. F. González, S. Nicolai, J. Waser, *Chem. Commun.* **2011**, *47*, 102–115.

[17]   A. A. Kantak, L. Marchetti, B. DeBoef, L. Ackermann, R. Vicente, A. R. Kapdi, D. Alberico, M. E. Scott, M. Lautens, X. Chen, et al., *Chem. Commun.* **2015**, *51*, 3574–3577.

[18]   K. Kiyokawa, T. Kosaka, T. Kojima, S. Minakata, *Angew. Chemie - Int. Ed.* **2015**,

54, 13719–13723.

[19]   A. Yoshimura, S. R. Koski, J. M. Fuchs, A. Saito, V. N. Nemykin, V. V. Zhdankin, *Chem. - A Eur. J.* **2015**, *21*, 5328–5331.

[20]   J. A. Souto, C. Martínez, I. Velilla, K. Muñiz, *Angew. Chemie - Int. Ed.* **2013**, *52*, 1324–1328.

[21]   A. A. Kantak, S. Potavathri, R. A. Barham, K. M. Romano, B. Deboef, *J. Am. Chem. Soc.* **2011**, *133*, 19960–19965.

[22]   J. Ciesielski, G. Dequirez, P. Retailleau, V. Gandon, P. Dauban, *Chem. - A Eur. J.* **2016**, *22*, 9338–9347.

[23]   N. V Tsarevsky, *J. Polym. Sci. Part A.* **2010**, *48*, 966–974.

[24]   D. Liu, C. W. Bielawski, *Polym. Int.* **2016**, *66*, 70–76.

[25]   V. Aureggi, G. Sedelmeier, *Angew. Chemie - Int. Ed.* **2007**, *46*, 8440–8444.

[26]   R. P. Singh, R. D. Verma, D. T. Meshri, J. M. Shreeve, *Angew. Chemie - Int. Ed.* **2006**, *45*, 3584–3601.

[27]   T. K. Achar, S. Maiti, P. Mal, *Org. Biomol. Chem.* **2016**, *14*, 4654–4663.

[28]   K. Morimoto, Y. Ohnishi, A. Nakamura, K. Sakamoto, T. Dohi, Y. Kita, *Asian J. Org. Chem.* **2014**, *3*, 382–386.

[29]   L. L. Z. Saginova, *Zhurnal Org. Khimii* **1979**, *15*, 1866–1871.

[30] V. V. Z. Bardin, *Zhurnal Org. Khimii* **1980**, *16*, 1256–1263.

[31] S. Sawaguchi, Masanori; Ayuba, Shinichi; Hara, *Synthesis (Stuttg).* **2002**, *13*, 1802–1808.

[32] N. N. Z. Zefirov, *Zhurnal Org. Khimii* **1989**, *25*, 1807–1808.

[33] R. Kumar, Y. Cao, N. V. Tsarevsky, *J. Org. Chem.* **2017**, *82*, 11806–11815.

[34] J. G. and A. Varvoglis, *J. Chem. Soc. Perkin Trans. 1* **1985**, *1985*, 757–763.

[35] A. A. Z. Mironova, *Zhurnal Org. Khimii* **1989**, *25*, 306–311.

[36] B. C. Schard, C. L. Hill, *Inorg. Chem.* **1983**, *22*, 1563–1565.

[37] V. Nikiforov, V. S. Karavan, S. A. Miltsov, S. I. Selivanov, E. Kolehmainen, E. Wegelius, M. Nissinen, *Arkivoc* **2003**, *2003*, 191.

[38] S. A. Moteki, S. Selvakumar, T. Zhang, A. Usui, K. Maruoka, *Asian J. Org. Chem.* **2014**, *3*, 932–935.

[39] Y. Y. Z. Shabarov, *Zhurnal Org. Khimii* **1981**, *17*, 1886–1892.

[40] and E. S. Jose I. Concepciõn, Cosme G. Francisco, Rosendo Herndndez, José A. Salazar, *Tetrahedron Lett.* **1984**, *25*, 1953–1956.

[41] P. de Armas, R. Carrau, J. I. Concepción, C. G. Francisco, R. Hernández, E. Suárez, *Tetrahedron Lett.* **1985**, *26*, 2493–2496.

CHAPTER 6.

MODIFICATION OF NATURAL RUBBER USING HV IODINE(III) COMPOUNDS CONTAINING TETRAZOLES

6.1. Introduction

6.1.1. Natural rubber (PIP)

The natural rubber is obtained from *Hevea brasiliensis*, contains 93-95% of cis-1,4-polyisoprene (PIP).[1] It is an unsaturated elastomer with many superior properties such as high strength, outstanding resilience, and high elongation at break.[2] However, PIP lacks in some properties such as oil and weather resistances. Moreover, the presence of the unsaturation of carbon-carbon double bonds in the PIP backbone causes easy degradation when PIP is exposed to sunlight, ozone, UV radiation and air, especially at high temperature.[3] Therefore, chemical modification of PIP is needed to overcome the disadvantages and to achieve more desirable properties. The chemical modification not only improves the interaction between the blend components but also compensates some of PIP drawbacks such as its resistance to ageing and to solvents or its gas impermeability.[4] Many types of chemical modification have been used, such as chlorination,[5] hydrogenation,[6] epoxidation,[7, 8] and grafting.[9] Because of the high reactivity of double bonds, an organic compound carrying functional groups can be easily grafted onto an olefin by various reactions such as electrophilic,[10] nucleophilic,[11] and radical addition reactions.[12, 13] The

reactivity, however, is often less in a polymer compared with a low molecular weight olefin, since the double bond in a macromolecule is less accessible than a structurally similar double bond in a molecule. The high sensitivity to changes in temperature[14] and the radical nature of the process,[15] leading to the occurrence of gelation reactions, hindered the wide introduction of the given method in the synthetic rubber industry. Thus, modification at low temperature and rapid reaction conditions might be the key to functionalize the PIP backbone without gelation. Moreover, the easy and quick modification of PIP with halogens like iodine and energetic molecule such as tetrazoles at the same time, without gelation, could be of interest to many industrialists, defense research agencies, and academic societies for the explosive or energetic characteristics of tetrazoles and opportunity to further modification of backbone via iodine functionality.

The modification of PIP with energetic molecules such as tetrazoles might find many applications in the fields of binders,[16] propellants,[17, 18] or high energy output materials.[19, 20] They offer interesting properties for the demands of new energetic polymers. They bring along a high nitrogen content (up to 79 % for 1H-tetrazole) and hence an environmental friendliness (due to their solely gaseous decomposition products N_2).[21] Additionally, they possess overall good thermal stabilities and considerable energetic properties.[22] They also offer high heats of formation but are more stable than azide groups.[23, 24] Hence, readily available polymers such as natural rubber functionalized with tetrazole groups are of interest of this article. These energetic polymers are promising but they come along with tedious methods to prepare them that is mostly with their synthetic routes that require high temperature, longer reaction time, synthesis of special monomers, which, similarly to other low molecular weight explosives, are often heat- or shock-sensitive, and therefore harmful to work with.

The organic compounds of polyvalent (III- or V-valent) iodine, also named HV iodine compounds (due to the special 3-center-4-electron bonds at the central halogen atom) have attained great importance in organic synthesis. Many of these compounds, including (diacyloxyiodo) arenes, $ArI(O_2CR)$, can serve as free radical precursors and have been successfully employed in a number of chemical transformations, including (pseudo)halogenation and tetrazolylation. Our group has reported the synthesis of various types of different HV iodine (III) compounds containing various tetrazoles and their use in the oxidative iodotetrazolylation reactions of styrene and cyclohexene as well as radical transfer of tetrazole groups to *N, N*-dimethylaniline. In this article, the iodotetrazolylation reactions is extrapolated to PIP to obtain ITZ-PIP. The reactivity at iodine site was further explored to prepare N_3TZ-PIP and methyl methacrylate (MMA) grafted brush polymers using ITP.
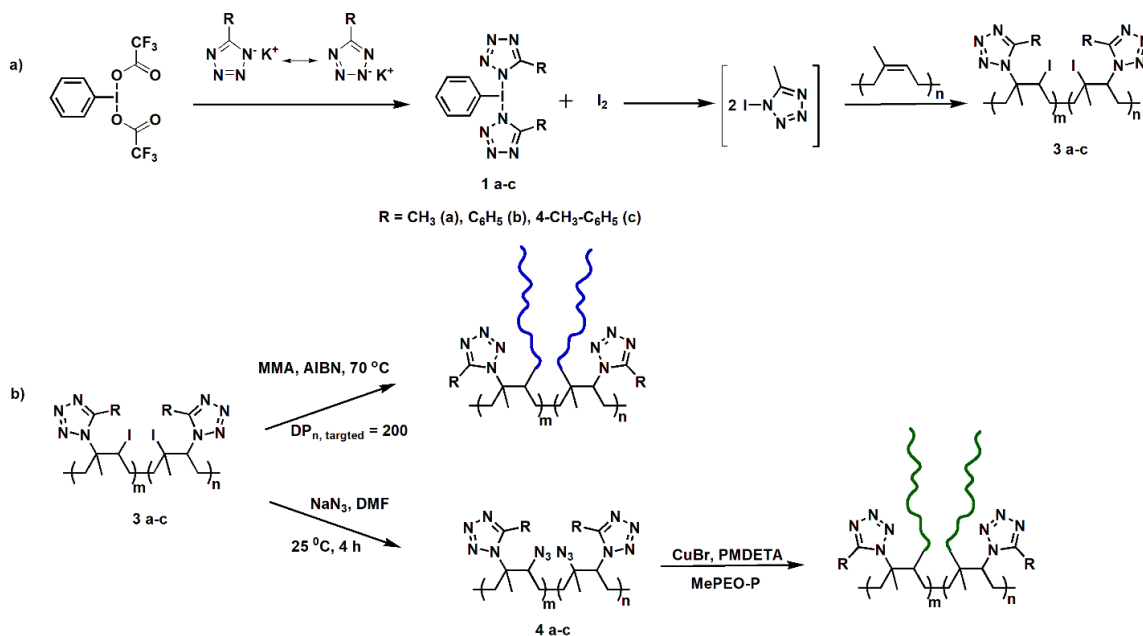
**Scheme 6-1.** Synthetic routes to modified PIP.

6.2. Results and Discussion

6.2.1. Synthesis of ITZ-PIP using HV iodine compounds 1a-c in the presence of I_2

The HV iodine (III) compounds **1a-c** were synthesized using the previously reported procedure (**Chapter 5** and **section 5-5-3**). Suarez and coworkers demonstrated the use of $PhI(O_2CCH_3)_2$-I_2 in the acetoxylation of various substrates, and the reaction was further implemented to the iodoacetoxylation of olefins. In our previous report, we also successfully reported the reaction of HV iodine (III) compounds containing various tetrazoles with cyclohexene and styrene in the presence of I_2 to yield iodotetrazolylated products. Similar iodotetrazolylation reactions between PIP and **1a-c** were carried out in the presence of stoichiometric I_2 in CH_2Cl_2 as shown in **Scheme 6-1**. Initially, HV iodine compounds were mixed with I_2 in CH_2Cl_2 to produce an intermediate adducts **2 a-c**, as shown in **Scheme 6-1**, that immediately reacts with the double bonds of PIP. Since the double bonds of the PIP are assymetric in nature, the addition reaction of the adducts **2 a-c** with the olefin group of PIP yielded asymmetric products, **3 a-c**. The obtained copolymers had a secondary and a tertiary iodine and tetrazole at the backbone of PIP.

R = CH$_3$ (a), C$_6$H$_5$ (b), 4-CH$_3$-C$_6$H$_5$ (c)
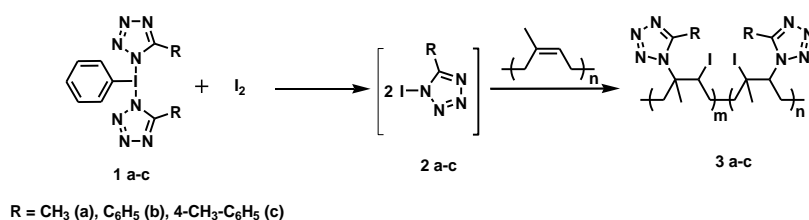
Scheme 6-2. Oxidative iodotetrazolylation of PIP in the presence of I_2 in CH_2Cl_2 at 25 ^{0}C.

Furthermore, iodine could be very easily be replaced with substituent such as azide, making the polymer more energetic in nature. Another advantage of the iodotetrazolylated modification in this work was that the reaction was completed in 15 min in all the cases, confirmed by ^{1}H NMR analysis. The reaction was kept for a longer time, 1 h, to eliminate the possibility of obtaining unreacted PIP. After 1 h, the polymers were individually purified by dialysis against acetone using a membrane with molecular weight cutoff of 500 Da (Spectrum Laboratories). The solvent was changed every 10−12 h for each and this was repeated ten times, and the polymer was obtained by evaporation of the solvent followed by dissolving the polymer in a minimum amount of CH_2Cl_2 and pouring into liquid nitrogen to obtain solvent free pure modified PIP with various tetrazoles and iodine. After the isolation of products **3a-c**, they were subjected to a substitution reaction of iodine to azide groups to obtain products **4a-c**. The substitution reaction was carried out with NaN_3 in DMF at room temperature for 4h and the polymers were isolated by precipitation in methanol-water (1:1, v/v) and analyzed by ^{1}H NMR in $CDCl_3$ and IR spectroscopy on KBr plates.

The ^{1}H NMR spectra for reaction between PIP and **1c** in the presence of I_2 was analyzed and it was found that the vinyl protons of PIP at 5.1 ppm disappeared in 1 h, as shown in **Figure 6-2-A**. The appearance of a peak, 5, at 4.5 ppm was for the proton next to the 5-(4-CH_3-C_6H_5) tetrazole and peak, 4, at 3.54 ppm is the result of the presence of iodine atom (**Figure 6-2-B**). The appearance of peaks 8 at 2.41 ppm, 9 at 7.23 ppm, and 10 at 8.00 ppm are the protons associated with the methyl, meta protons, and ortho protons of 5-(4-CH_3-C_6H_5) of tetrazole respectively (**Figure 6-2-B**). Furthermore, after the substitution reaction of iodine group in **3c** with N_3-group using NaN_3 in DMF at room temperature it was found that the peak 4 at 3.54 ppm was disappeared and a new peak 11 at 2.57 ppm appeared due to the proton next to the N_3-group appeared. Also,

there was a new peak 13 at 5.82 ppm appearing which might be a result of the vinyl protons due to the elimination reaction, as shown in **Figure 6-2**.
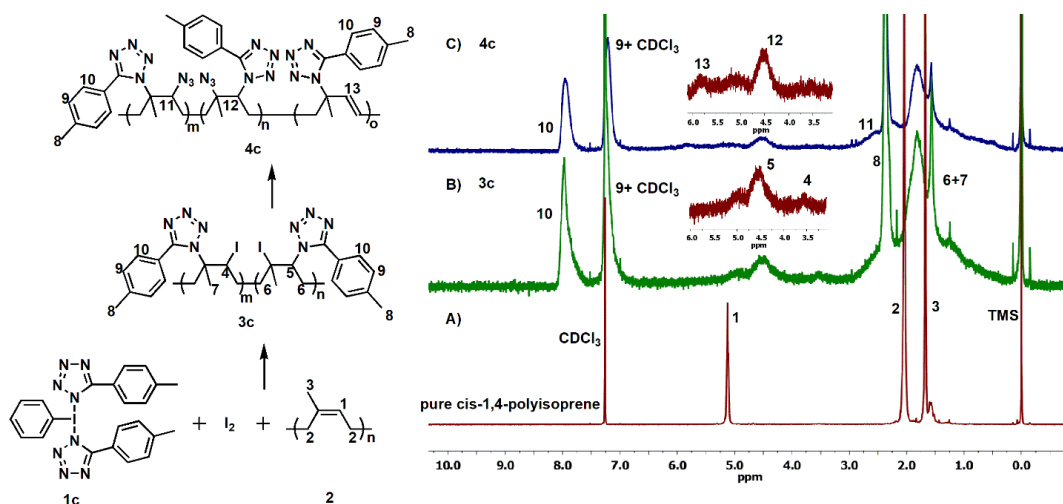

Figure 6-1. ^{1}H NMR spectra overlay for the modification of cis-1,4-polyisoprene with peak assignments. Spectrum A) represents the pure cis-1,4-polyisoprene, B) the ^{1}H NMR spectrum of iodotetrazolylation product **3c**, and C) the ^{1}H NMR spectrum of polymer with tetrazole and azide **4c**.

The polymers **3c** and **4c** were further analyzed using FT-IR spectroscopy and compared with the pure PIP. As shown in the **Figure 6-3**, for polymer **3c**, the disappearance of the characteristic peaks of PIP at 2966 cm^{-1} (=C-H stretch), 2917 and 2848 cm^{-1} (-C-H stretch), 1660 cm^{-1} (alkenyl C=C stretch), 834 cm^{-1} (=C-H bending) and appearance of new peaks at 1614 cm^{-1} (aromatic C=C stretch), 820 cm^{-1} and 757 cm^{-1} (aromatic C-H bending) further proves that the iodotetrazolylation reaction was successfully achieved with the disappearance of all the starting material.
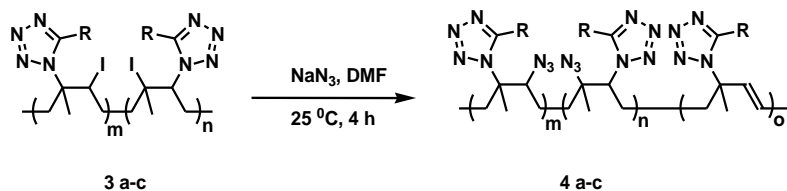
Scheme 6-3. Synthetic route to modify cis-1,4-polyisoprene to incorporate various tetrazoles and azide groups.

The intense absorbance at ca. 2100 cm^{-1} of that functionality, corresponding to the azide asymmetric stretching vibration appears for the polymer **4c** further proving the substitution of iodine to azide groups.
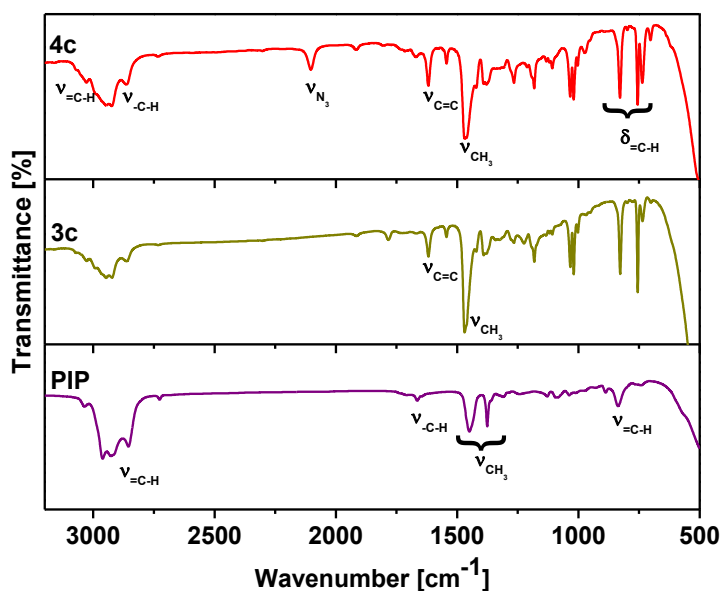

Figure 6-2. IR spectra (films cast on KBr plates) for the pure cis-1,4-polyisoprene, polymer **3c**, and polymer **4c** with the assignment of frequencies.

To further verify the presence of azide groups in the polymers and to demonstrate the utility of the presented reaction for further functionalization, the polymers were reacted with an alkyne-

terminated poly(ethylene oxide) under ''click'' chemistry conditions with a Cu(I)-based catalyst to yield polymeric brushes with hydrophilic side chains and a hydrophobic backbone (**Scheme 6-1 (b)**). The grafting-onto functionalization of polymers with azide groups using the same PEO derivative as in this work, MePEO-P, has been reported. The click reactions were carried out at r.t. in DMF using CuBr as the catalyst under a nitrogen atmosphere. **Figure 6-4** shows the SEC profiles of the mixtures of N_3TZ-PIP and MePEO-P before the reaction and after 20 h at which point PMDETA was added and the reaction was continued further for 2 h. After 2 h, that is 22 h for the whole reaction, the significant decrease in the intensity of SEC peak for MePEO-P and a shift towards the higher molecular weight of N_3TZ-PIP confirmed the occurrence of the click reaction.
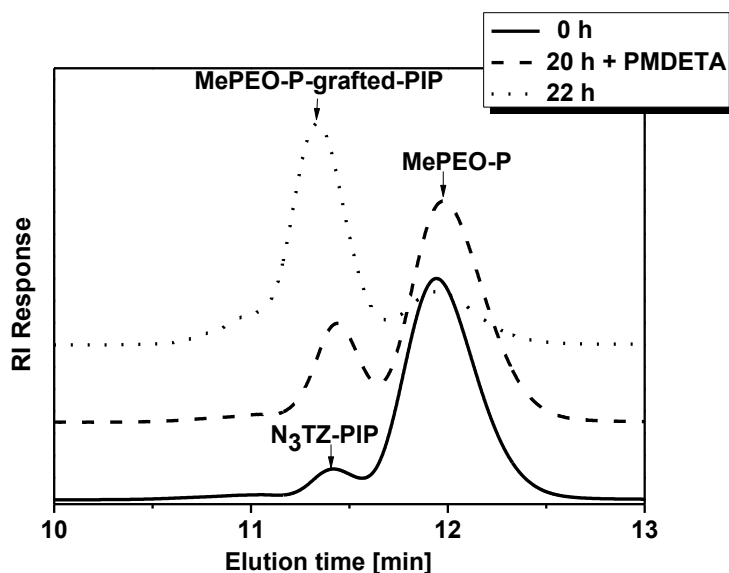

Figure 6-3. Click grafting reaction of MePEO-P onto N_3TZ-PIP at different time interval. At 20 h, PMDETA was introduced as a ligand to increase the redox potential of Cu(I)Br.

In our next attempts, iodine functionality was further explored by using it as initiating site for the ITP reaction to graft polymethyl methacrylate (polyMMA). The ITP reactions were done

under bulk and solution conditions at 70 ^{0}C. When compared, as expected the rate of polymerization in bulk ITP (**Table 6-1**, entry 1) was faster than the rate of polymerization in solution (**Table 6-1**, entry 2) as shown in **Figure 6-5 (a)**.

Table 6-1. Graft polymerization of MMA onto **3c** under ITP

#	Solvent	[MMA]$_0$ / [3c]$_0$ / [AIBN]$_0$	T [h]	Conv [%]	M$_n$	PDI
1	Bulk	200 / 1 / 0.2	2	37	83,000	1.58
2	DMAc	200 / 1 / 0.2	9	29	24,500	1.59

To begin the investigation, MMA was polymerized in bulk and DMAc at 70 ^{0}C using **3c** as the macro-CTA with the degree of polymerization at complete monomer conversion (DP$_{n,targ}$ = [MMA]$_0$ / [**3c**]$_0$) set to 200, and with 20 mol % AIBN relative to macro-CTA, acting as the additional radical source (**Figure 6-5**). The monomer conversion was periodically determined by integrating the ^{1}H NMR signals of the vinyl and methyl hydrogen atoms. The first-order kinetic plot (**Figure 6-5 (a)**) was linear that indicates the constant generation of polymeric radicals. The polymerization was well-controlled, as indicated by the linear increase of M$_{n,app}$ and decrease in PDI with conversion (**Figure 6-5 (b)**). The molecular weight distribution (MWDs) remained narrow and symmetric for both bulk and solution (**Figure 6-6 (a)** and (**b**)) and shifted smoothly towards higher molecular weights proving that the polymer **3c** efficiently exchanged between propagating and dormant chains. The brush polymers were isolated as described in the synthetic procedure and were subjected to TGA analysis and compared with pure polyMMA. It was found that the TGA curves for both brush and polyMMA were similar (**Figure 6-7**) and that could

because of dense grafting of polyMMA onto the backbone of polymer **3c**. This again proves the presence of iodine mostly at each alternate carbon in the **3c** backbone and the efficiency of ITP reaction.

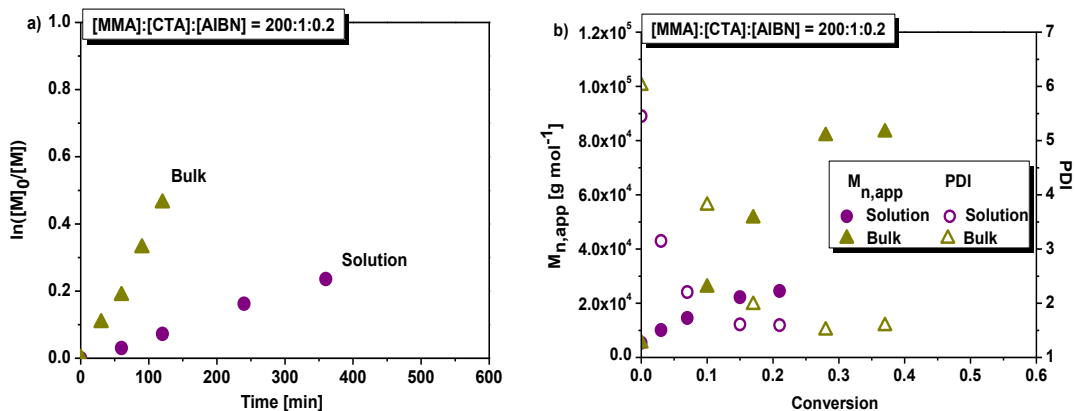**Figure 6-4.** The kinetics of the synthesis of brush polymer at the surface of iodotetrazolylated cis-1,4-polyisoprene using 20 % AIBN vs. ITZ-PIP in bulk and in DMAc (a) and (b) the evolution of apparent molecular weights and polydispersity index over conversion.
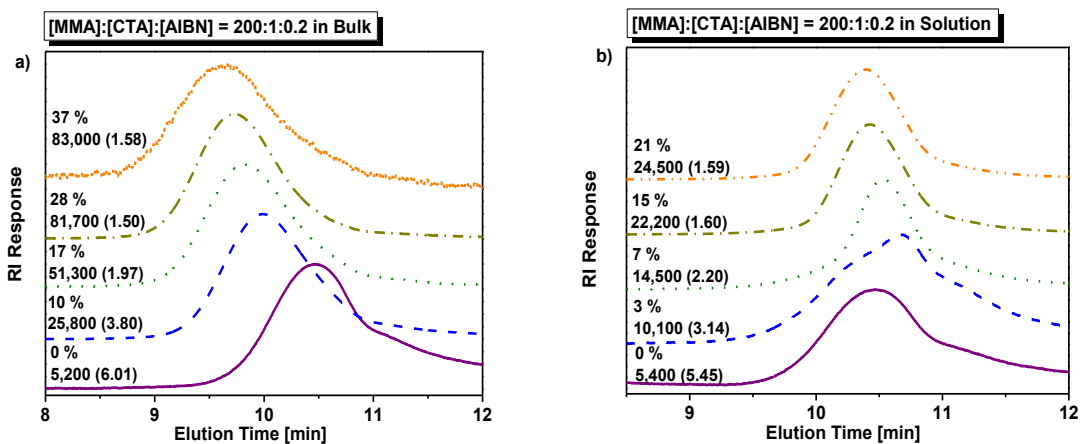

Figure 6-5. Evolution of GPC traces during the synthesis of brush polymer using 20 % AIBN vs. macro-CTA in bulk (a) and (b) in DMAc.

6.3. Experimental

6.3.1. Materials

5-Methyl-1H-tetrazole (Alfa Aesar, 97%), 5-phenyl-1H-tetrazole (Alfa Aesar, 99%), 5-(p-tolyl)-1H-tetrazole (TCI, 98%), [bis- (trifluoroacetoxy)iodo]benzene (PhI(O_2CCF_3)$_2$, Acros, 98%), polyisoprene (Aldrich, average M_w ~38,000 by GPC), I_2 (Sigma-Aldrich, 99.8%), CuBr (99.99%, Aldrich), NaN_3 (99.9%, Sigma-Aldrich), K_2CO_3 (Sigma-Aldrich, 99.8%) and solvents, including methylene chloride (Fisher, 99.5%), methanol (Fisher, 99.8%), acetone (Fisher, 99.8%) and N,N-dimethylformamide (DMF, 98%, EMD Millipore), and were used as received. The deuterated solvent, CDCl$_3$, (99.8% D, Cambridge Isotope Laboratories) contained a small amount of tetramethylsilane (TMS) as a chemical shift reference. Poly(ethylene oxide) monomethyl ether 4-pentynoate (MePEO-P, M_n = 2,000 g mol^{-1}) was synthesized by esterification of the polymeric alcohol, MePEO-OH, with 4-pentynoic acid. HV iodine(III) reagents were synthesized according to a recently reported procedure from our lab.

6.3.2. Instrumentation and analysis

To monitor the progress of the ITP reactions, samples were withdrawn periodically using a nitrogen-purged syringe. Part of each sample was diluted with CDCl$_3$ (containing a small amount of tetramethylsilane as the chemical shift reference) for NMR analysis (determination of conversion), which was carried out on a Bruker Avance DRX (400 MHz) spectrometer. Another part of the sample was diluted with THF and filtered through an Acrodisc 0.2 µm PTFE syringe filter, and the solution was subjected to size exclusion chromatography (SEC) analysis. Molecular weights (number-average (M_n) and weight-average (M_w)) and molecular weight distribution dispersities (Đ = M_w/M_n) were determined by SEC on a Tosoh EcoSEC system equipped with a

series of 4 columns (TSK gel guard Super HZ-L, Super HZM-M, Super HZM-N, and Super HZ2000) and using THF as the eluent (30 °C) and a refractive index detector. The SEC instrument was calibrated using a series of linear polySty standards. Infrared (IR) spectra were collected on a Thermo Scientific Nicolet iS10 FT-IR Spectrometer. The samples were prepared by dissolving 100 mg of polymer in 2 mL of chloroform, followed by casting a film on a KBr plate by slow evaporation of the solvent (achieved by covering the salt plate with the polymer solution with a beaker). ^{1}H (64 scans) and ^{13}C NMR spectra (10,000−15,000 scans) of the purified polymers (ca. 0.2 g in 0.6 mL of CDCl$_3$ containing tetramethylsilane, TMS) were acquired on the spectrometer mentioned above.

6.3.3.   Reaction of 1a, 1b, or 1c with PIP in the presence of I$_2$

In a 250 mL beaker, PIP (10 g, 0.147 mol) was dissolved in CH$_2$Cl$_2$ (100 mL) to make the stock solution of PIP. Then, in a 100 mL reaction tube, a stir bar was placed followed by **1c** (7.67 g, 14.7 mmol) and the tube was wrapped with aluminum foil to protect the contents from light. Then, CH$_2$Cl$_2$ (10.0 mL) was added and the tube was immersed in a water bath at 25 °C and stirred until the solution became clear (ca. 30 min). Then, I$_2$ (3.73 g, 14.7 mmol) was added and the clear solution turned turbid white. This heterogeneous solution was stirred for another 5 min. and PIP (1.0 g, 14.7 mmol, in 10.0 mL CH$_2$Cl$_2$) was added using a syringe. It was noted that upon the addition of PIP the color turned brown and the solution remained heterogeneous. After 1 h of stirring at room temperature, the solvent was evaporated under reduced pressure. The obtained brown solid was dissolved in acetone (10.0 mL) and dialyzed against acetone using a membrane with molecular weight cutoff of 500 Da (Spectrum Laboratories). The solvent was changed every 10−12 h and this was repeated six times, and the polymer was obtained by evaporation of the

solvent. The corresponding iodotetrazolylated PIP were precipitated from CH_2Cl_2 solutions in methanol-water mixture (1:1, v/v) and dried in vacuum for 12 h to obtain a light brown powder. The similar experiments were done with **1a** and **1b** under similar reaction conditions.

6.3.4. Substitution reaction of iodine in iodotetrazolylated PIP, 3a-c, with azide groups

In a 10 mL test tube equipped with a stir bar, **3c** (3.7 g, 9.6 mmol) was dissolved in DMF (2.0 mL) and NaN_3 (1.25 g, 19.0 mmol, 2 equiv. with respect to each iodine atom in **3c**) was added. The reaction mixture was allowed to stir for 4h while monitoring the reaction by ^{1}H NMR. Finally, the reaction mixture was precipitated in methanol-water mixture (1:1, v/v) to yield a light brown powder which was then dried in vacuum for 12 h.

6.3.5. Click chemistry-type grafting onto azidated PIP

In a 10 mL reaction tube equipped with a magnetic stir bar, **4c** (100 mg, 0.37 mmol) and CuBr (10 mg, 74.3 µmol, 20 mol % vs. **4c**), were added and the tube was capped with a rubber septum and secured with electric tape. The tube was evacuated and backfilled with nitrogen five times. Deoxygenated DMF (0.5 mL) was injected with a nitrogen purged syringe, and the mixture was stirred until the solution was formed. Then, deoxygenated MePEO-P (0.7 g, 0.37 mmol) was added using a nitrogen-purged micro syringe, and the solution turned yellow. The reaction mixture was stirred at r.t. and samples were taken in 12 h, 20 h (at this time PMDETA (31.0 µL, 0.15 mmol) 40 mol% vs **4c** was added) and 22 h, which were diluted with THF and analyzed by SEC.

6.3.6.   Grafting of MMA onto iodotetrazolylated PIP using ITP

To a 10 mL reaction tube, **4c** (34 mg, 0.094 mmol, 1 eq.) and AIBN (3 mg, 0.019 mmol, 0.2 eq.) were added followed by dissolving the solids in MMA (2.0 mL, 18.7 mmol, 200 eq.). The homogeneous solution was purged with nitrogen for 15 min while the tube was immersed in an ice-water bath followed by placing the reaction tube in an oil bath preheated to 70 ^{0}C. Samples were withdrawn periodically to determine the monomer conversion by ^{1}H NMR (ca. 0.05 mL of the polymer solution was dissolved in 0.5 mL CDCl$_3$) and the molecular weights and PDI evolution by GPC (ca. 0.05 mL polymer solution was dissolved in THF and passed through a 0.2 µm PTFE syringe filter). The final polymer was dissolved in DCM (approximately 1.8 mL of the polymer solution in 10 mL of DCM) and precipitated in diethyl ether (100 mL). The polymer was redissolved in DCM and reprecipitated in ether and this was repeated for three times. The isolated polymer was dried in vacuum for 12 h. The similar reaction was carried out in the presence of 1:1 (v/v) DMAc and anisole (2 mL) vs. MMA.

6.4.   Conclusion

The oxidative iodotetrazolylation reactions of PIP was performed under mid conditions and were found to be efficient. The iodotetrazolylation reaction time was less than an hour and no gelation was found during the reaction. The products were characterized by ^{1}H, ^{13}C NMR and IR spectroscopy, GPC, DSC, and TGA. The iodine group was further utilized to functionalize the PIP backbone with azide groups and the combination of azide and tetrazole were found to be exothermic during the SDT analysis. The azidation reaction was not found to be inefficient as most of the iodine was present at tertiary position and the secondary position. The iodine functionality

was further explored with the ITP reaction where iodine was used as the initiating site for grafting polyMMA. The modification of PIP was found efficient throughout the study.

6.5.   References

1.   A. S. Dunn, *Concise encyclopedia of polymer science and engineering*, 1991, **25**, 1015.

2.   N. Platzer, *Journal of Polymer Science Part C: Polymer Letters*, 1986, **24**, 492.

3.   P. Wongthong, C. Nakason, Q. Pan, G. L. Rempel and S. Kiatkamjornwong, *European Polymer Journal*, 2013, **49**, 4035-4046.

4.   S. Benmesli and F. Riahi, *Polymer Testing*, 2014, **36**, 54-61.

5.   J.-P. Zhong, S.-D. Li, Y.-C. Wei, Z. Peng and H.-P. Yu, *Journal of Applied Polymer Science*, 1999, **73**, 2863-2867.

6.   A. Mahittikul, P. Prasassarakich and G. L. Rempel, *Journal of Applied Polymer Science*, 2006, **100**, 640-655.

7.   I. R. Gelling, *Rubber Chemistry and Technology*, 1985, **58**, 86-96.

8.   C.-C. Peng and V. Abetz, *Macromolecules*, 2005, **38**, 5575-5580.

9. N.-J. Huang and D. C. Sundberg, *Journal of Polymer Science Part A: Polymer Chemistry*, 1995, **33**, 2587-2603.

10. I. A. Christopher, *Chemical Engineering & Process Techniques*, 2017, **3**, 1041.

11. Y. H. a. P. Kim, A., *Macromolecules*, 1991, **24**, 6505–6511.

12. D. S. Campbell, in *Developments in Crop Science*, eds. M. R. Sethuraj and N. M. Mathew, Elsevier, 1992, vol. 23, pp. 451-486.

13. J. J. Reisinger and M. A. Hillmyer, *Progress in Polymer Science*, 2002, **27**, 971-1005.

14. D. P. Derouet, P.; Boccaccio, G.;And Brosse, J.C., *Journal of Natural Rubber Research*, 1991, **6**, 39-54.

15. D. M. Preiss, W. M. Sawyer and W. C. Simpson, *Journal of Applied Polymer Science*, 1963, **7**, 1803-1814.

16. D. Ginsburg, *Israel Journal of Chemistry*, 1964, **2**, 367-367.

17. A. Provatas, *Energetic Polymers and Plasticisers for Explosive Formulations – A Review of Recent Advances*, 2000.

18. A. J. Paraskos, in *Energetic Materials: From Cradle to Grave*, eds. M. K. Shukla, V. M. Boddu, J. A. Steevens, R. Damavarapu and J. Leszczynski, Springer International Publishing, Cham, 2017, DOI: 10.1007/978-3-319-59208-4_4, pp. 91-134.

19. A. D. Kshirsagar, D. G. Hundiwale, V. V. Gite and P. P. Mahulikar, *Chemistry of Heterocyclic Compounds*, 2017, **53**, 1090-1093.

20. M. Nabati, A. Latifpour and J. Aboudi, *Designed Monomers and Polymers*, 2014, **17**, 453-457.

21. P. Singh Rajendra, D. Verma Rajendar, T. Meshri Dayal and M. Shreeve Jean'ne, *Angew. Chem. Int. Ed.*, 2006, **45**, 3584-3601.

22. R. N. Butler, in *Comprehensive Heterocyclic Chemistry II*, eds. A. R. Katritzky, C. W. Rees and E. F. V. Scriven, Elsevier, Oxford, 1996, vol. 4, pp. 621-678.

23. V. A. Ostrovskii, G. I. Koldobskii and R. E. Trifonov, in *Comprehensive Heterocyclic Chemistry III*, eds. A. R. Katritzky, C. A. Ramsden, E. F. V. Scriven and R. J. K. Taylor, Elsevier, Oxford, 2008, vol. 4, pp. 257-423.

24. R. N. Butler, in *Comprehensive Heterocyclic Chemistry, 4A*, eds. A. R. Katritzky and C. W. Rees, Pergamon, Oxford, 1984, vol. 5, pp. 791-838.