Determination of ATRP Equilibrium Constants under Polymerization Conditions

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Experimental Part

Materials

Methyl acrylate (MA 99+%, Aldrich) were passed through a column filled with basic alumina prior to use. Ethyl 2-bromopropionate (EBrP 99%, Aldrich), methyl 2-bromopropionate (MBrP 98%, Aldrich), Cu^IBr (99.999%, Aldrich), Cu^{II}Br₂ (99.999%, Aldrich), tris(2-pyridylmethyl)amine (TPMA 99%, ATRP solutions), tris[2-(dimethylamino)ethyl]amine (Me₆TREN 99%, ATRP solutions), acetonitrile (MeCN 99.8%, Aldrich) and dimethyl sulfoxide (DMSO >99.5%, Aldrich) were used as received.

Characterization

UV/Vis/NIR measurements: All spectroscopic measurements were performed on a Varian Cary 5000 UV/Vis/NIR spectrometer. A flask containing Cu^IBr (8.0 mg), Cu^{II}Br₂ (12.4 mg) and TPMA (38.7 mg) was sealed and degassed by allowing N₂ to flow through it for 1 h. 10 mL DMSO, which was bubbled with N₂ for 1 h, was added to this flask. MA was degassed via bubbling of N₂ as well. A Schlenk flask with a magnetic stirrer was closed with a stopper attached to a quartz cuvette (1 cm path length), and evacuated then backfilled with nitrogen several times. 3 mL of the stock solution with Cu species and 3 mL MA were added to the Schlenk flask with a syringe. One spectrum was taken and recorded as time 0. Finally, 4.3 μ L EBrP was added to the reaction mixture with a micro syringe. The Schlenk flask was placed in a 25 °C oil bath. Spectra were taken every 10 min. The change in Cu^{II} concentration was

followed at $\lambda = 960$ nm. The conversion of monomer was calculated by integration from $\lambda = 1610$ to 1625 nm.

Stopped-flow measurements: $[Cu^I]$ decrease and $[Cu^{II}]$ increase were followed with a stopped-flow apparatus consisting of a BioLogic Science Instruments MOS450 monochromator, equipped with a 150W Xe lamp and a photomultiplier 400, and a SFM20 stopped-flow module, equipped with two 10 mL gas-tight Hamilton syringes. Data acquisition and analysis was done with Bio-Kine 4.2. All kinetics was measured at 25°C in degassed DMSO in a FC15 cuvette with an optical path length of 1.5 mm. The dead time was determined by conventional methods to be 5.3 ms. For every measurement a total volume of at least 0.24 mL was pushed through the cuvette with a flow–rate of 7 mL/s. The measurements were performed by following the absorbance at 405 nm where Cu^{II}Br₂/L, Cu^IBr/L, L, and alkyl halide (RX) could possibly have certain absorbance. The concentration of ligand would not change during the measurement, while the increase of Cu^{II}Br₂/L equals to the decrease of Cu^IBr/L and RX. Thus, Δ absorbance = [ϵ (Cu^{II}) – ϵ (Cu^I) – ϵ (RX)] Δ [Cu^{II}].

Stock solutions of Cu^IBr (28.7 mg in 10 mL DMSO, 20 mM), TPMA (66.8 mg in 10 mL DMSO, 23 mM) and MBrP (33.4 mg in 10 mL DMSO, 20 mM) were prepared separately. The first syringe of the SFM 20 contained a 10 mM solution of Cu^I/TPMA, prepared by adding 5 mL of each respective stock solution, and the second syringe contained a 20 mM MBrP solution. A [Cu^{II}] increase was measured at 405 nm. K_{ATRP} was determined from the slope (m) of an F(Y) versus time (t) plot using the formula $K_{\text{ATRP}} = (\text{m}/2k_1)^{1/2}$ with $Y = [\text{Cu}^{II}]$ and $k_t = 0.8 \times 10^9 \text{ M}^{-1} \text{ s}^{-1}$ for DMSO at 25 °C. It was assumed that only activation, deactivation, and termination events took place. All solutions and syringes were degassed by repetitive FPT cycles before and after addition of the respective compound. The K_{ATRP} value of Cu^I/Me₆TREN in DMSO was measured via the same procedure.

Additional data

UV/NIR spectra of the reaction mixture



Figure S1. (a) UV/Vis/NIR spectra of Cu^{II}Br₂/TPMA in DMSO/MA = 1/1 (v/v) mixture, pure DMSO and pure MA. The change in Cu^{II} concentration was followed at $\lambda = 960$ nm. The conversion of monomer was calculated by integration from $\lambda = 1610$ to 1625 nm. The same method was already reported in literature.¹ (b) The evolution of Cu^{II} species and (c) the conversion of monomer in ATRP of MA in MA/DMSO = 1/1 (v/v) with the ratio of reagents [MA]:[EBrP]:[Cu^{II}Br]:[Cu^{II}Br₂]:[TPMA] = 1000:1:0.5:0.5:1.2, at 25 °C.

Solvent effect on k_p values

Most conventional organic solvents do not significantly affect the rate coefficient of radical propagation. However, more polar solvents have larger impact, for example, the k_p values increase 60% in DMSO, as compared to bulk polymerization of methyl methacrylate (MMA) at 26.5 °C.² The k_p values change linearly with the fraction of solvent.³ MeCN is less polar than DMSO, thus the effect on k_p should be smaller. The $k_p/k_{p,bulk}$ values of methacrylates where previously correlated with Kamlet-Taft solvatochromic parameters (equation S1), which are 2.4 for DMSO and 1.3 for MeCN at 25 °C, as listed in Table S1.^{4,5}

$$\ln(k_{\rm p}/k_{\rm p,\,bulk}) = \ln(k_{\rm p}/k_{\rm p,\,bulk})^0 + s\pi^* + a\alpha + b\beta \tag{S1}^4$$

Table S1. Solvent effect on k_p values of MMA.

Entry	Solvent	π^*	α	β	$k_{\rm p}/k_{\rm p,bulk}$	r
1	DMSO	1.04	0.18	0.71	2.4	1.4
2	MeCN	0.75	0.19	0.31	1.3	0.3

 $k_p/k_{p,bulk}$ values were calculated by applying equation S1, where $\ln(k_p/k_{p,bulk})^0 = -1.27$, s = 1.72, a = 0.63, b = 0.37, at 25 °C and $r = k_p/k_{p,bulk} - 1.4$ The propagation rate coefficient values in certain volume fraction of solvent were calculated as $k_{p,s} = k_{p,bulk} * (1+r*f_s)$.

Determination of *K***ATRP during polymerization**

In literature, there are no reports on solvent effects on k_p of MA. Thus, although solvents effects might be dissimilar, the K_{ATRP} values were calculated, using values r = 1.4 and 0.3 for k_p of MMA (Table 1). The calculated K_{ATRP} values are presented in Tables S2 and S3 for TPMA and Me₆TREN ligands in MeCN and in Tables S4 and S5 for TPMA and Me₆TREN ligands in DMSO, correspondingly.

Entry	Т	fs	[MA]:[EBrP]:[Cu ^I]:[Cu ^{II}]:[L]	[EBrP]	-dln[M]/dt	K _{ATRP}	K _{ATRP,s}
	(°C)			(mM)	(s^{-1})		
1	0	0.50	200:1:0.1:0.097:0.24	27.8	1.8×10^{-6}	7.8×10 ⁻⁹	6.8×10 ⁻⁹
2	0	0.50	200:1:0.05:0.0485:0.12	27.8	1.7×10^{-6}	7.3×10 ⁻⁹	6.4×10 ⁻⁹
3	25	0.50	200:1:0.2:0.2:0.48	27.8	1.0×10 ⁻⁵	2.2×10^{-8}	2.0×10 ⁻⁸
4	25	0.50	200:1:0.1:0.1:0.24	27.8	1.2×10^{-5}	2.7×10^{-8}	2.4×10^{-8}
5	25	0.50	200:1:0.05:0.05:0.12	27.8	1.1×10^{-5}	2.5×10^{-8}	2.2×10^{-8}
6	25	0.67	133:1:0.1:0.1:0.24	27.8	2.9×10^{-5}	6.5×10^{-8}	5.4×10 ⁻⁸
7	25	0.33	267:1:0.08:0.08:0.192	27.8	4.3×10 ⁻⁶	9.7×10 ⁻⁹	8.8×10^{-9}
8	40	0.50	200:1:0.1:0.1:0.24	27.8	4.1×10^{-5}	6.7×10^{-8}	5.8×10 ⁻⁸
9	40	0.50	200:1:0.05:0.05:0.12	27.8	3.7×10^{-5}	6.0×10^{-8}	5.3×10 ⁻⁸
10	40	0.50	200:1:0.2:0.1:0.36	27.8	7.8×10 ⁻⁵	6.4×10 ⁻⁸	5.5×10 ⁻⁸
11	60	0.50	200:1:0.05:0.1:0.18	27.8	6.6×10 ⁻⁵	1.4×10^{-7}	1.2×10^{-7}
12	60	0.50	200:1:0.05:0.1:0.18	27.8	4.4×10^{-5}	9.6×10 ⁻⁸	8.3×10 ⁻⁸
13	60	0.50	200:1:0.025:0.05:0.09	27.8	6.8×10 ⁻⁵	1.5×10 ⁻⁷	1.3×10 ⁻⁷

Table S2. Polymerization of MA in MeCN with TPMA as the ligand.

 K_{ATRP} values were calculated by assuming constant k_p values at each temperature, $k_p = 8.1 \times 10^3$, 1.6×10^4 , 2.2×10^4 and 3.3×10^4 M⁻¹ s⁻¹ at 0, 25, 40 and 60 °C. $K_{\text{ATRP,s}}$ values were calculated considering the possible solvent effect on k_p , i.e., $k_{p,s} = k_p^*(1+0.3f_s)$.

Entry	$f_{\rm S}$	[MA]:[EBrP]:[Cu ^I]:[Cu ^{II}]:[L]	[EBrP]	-dln[M]/dt	K _{ATRP}	K _{ATRP,s}
			(mM)	(s^{-1})		
1	0.33	1000:1:0.5:0.5:1	7.40	1.7×10^{-5}	1.4×10^{-7}	1.3×10^{-7}
2	0.50	1000:1:0.4:1.6:2.4	5.55	5.0×10 ⁻⁶	2.2×10^{-7}	2.0×10^{-7}
3	0.67	200:1:0.05:0.94:1.19	27.8	1.7×10^{-5}	7.2×10^{-7}	6.0×10^{-7}

Table S3. Reactions in MeCN with Me₆TREN as the ligand at 25 °C.

 K_{ATRP} values were calculated by assuming constant k_p value as $1.6 \times 10^4 \text{ M}^{-1} \text{ s}^{-1}$ at 25 °C. $K_{\text{ATRP,s}}$ values were calculated considering the possible solvent effect on k_p , $k_{p,s} = k_p * (1+0.3f_s)$.

Entry	fs	[MA]:[EBrP]:[Cu ^I]:[Cu ^{II}]:[L]	[EBrP]	-dln[M]/dt	$K_{\rm ATRP}$	K _{ATRP,s}
			(mM)	(s^{-1})		
1	0.50	200:1:0.1:0.1:0.24	27.8	1.1×10^{-4}	2.5×10^{-7}	1.4×10^{-7}
2	0.67	1930:1:0.96:0.93:2.27	1.92	6.2×10^{-5}	2.0×10^{-6}	1.0×10^{-6}
3	0.83	4460:1:0.93:1.26:2.63	0.83	7.6×10^{-5}	7.7×10 ⁻⁶	3.6×10 ⁻⁶

Table S4. Reactions in DMSO with TPMA as the ligand at 25 °C.

 K_{ATRP} values were calculated by assuming constant k_p value as $1.6 \times 10^4 \text{ M}^{-1} \text{ s}^{-1}$ at 25 °C. $K_{\text{ATRP,s}}$ values were calculated considering the possible solvent effect on k_p , $k_{p,s} = k_p * (1+1.4f_s)$.

Table S5. Reactions in DMSO with Me₆TREN as the ligand at 25 °C.

Entry	fs	[MA]:[EBrP]:[Cu ^I]:[Cu ^{II}]:[L]	[EBrP]	-dln[M]/dt	K _{ATRP}	K _{ATRP,s}
			(mM)	(s^{-1})		
1	0.33	1000:1:0.3:0.7:1	7.40	4.4×10^{-5}	8.7×10^{-7}	5.9×10 ⁻⁷
2	0.50	1000:1:0.4:1.6:2.4	5.55	8.1×10 ⁻⁵	3.6×10 ⁻⁶	2.2×10^{-6}
3	0.67	1000:1:0.4:1.6:2.4	3.70	1.6×10^{-4}	1.1×10^{-5}	5.6×10 ⁻⁶

 K_{ATRP} values were calculated by assuming constant k_p value as $1.6 \times 10^4 \text{ M}^{-1} \text{ s}^{-1}$ at 25 °C. $K_{\text{ATRP,s}}$ values were calculated considering the possible solvent effect on k_p , $k_{p,s} = k_p * (1+1.4f_s)$.

Since the solvent alters K_{ATRP} values as largely as $10^2 \sim 10^4$ times but it affects k_p less than 2 times, the linear fitting of the $K_{\text{ATRP,s}}$ values gives only very minor changes from the case, assuming constant k_p values. In all experiments, the conversion of monomer was limited as 5~15%, where the contribution of termination could be neglected. For example in entry 3 Table S2 the conversion reached 6.5% in 2 h. During this time period, the absorbance of Cu^{II} species increased from 1.184 (5.55 mM) to 1.199 (5.70 mM). The molar percentage of dead chains was $T_{\text{mol}\%} = 0.56\%$, and the change in [Cu^I]/[Cu^{II}] was insignificant. In a faster polymerization, entry 10 Table S2, the conversion of monomer achieved 11.5% in 0.5 h, while $T_{\text{mol}\%} = 0.68\%$ with the absorbance of Cu^{II} changed from 0.586 (2.78 mM) to 0.606 (2.87 mM).

Determination of *K*_{ATRP} in DMSO via stopped flow

The determination of K_{ATRP} of Cu^IBr/TPMA in DMSO was performed at 5 mM [Cu^IBr/TPMA] and 10 mM [MBrP]. The K_{ATRP} value was calculated as 2×10^{-5} via a modified Fisher's F(Y) equation, Figure S2.⁶

$$F(Y) = \int_{0}^{Y} \frac{Y^{2}}{(I_{0} - Y)^{2} (C_{0} - Y)^{2}} dY = 2k_{t} K_{ATRP}^{2} t$$
(S2)

where *Y* is the concentration of $[Cu^{II}]$, I_0 is the initial concentration of MBrP, C_0 is the initial concentration of $[Cu^{I}]$. The $k_t = 8.4 \times 10^8$ in DMSO was taken from literature report.⁷



Figure S2. Determination of K_{ATRP} value of Cu^IBr/TPMA in pure DMSO with MBrP as the initiator (a) the evolution of Cu^{II} species; and (b) F(*Y*) function vs time at 25 °C.

The determination of K_{ATRP} of Cu^IBr/Me₆TREN in DMSO was performed with 5 mM [Cu^IBr/Me₆TREN] and 10 mM [MBrP]. The K_{ATRP} value was calculated as 2×10^{-4} , Figure S3. This value is 40 times smaller than estimated from electrochemical method using ethyl 2-bromoisobutyrate.⁸ This should be due to a more reactive alkyl halide used and also electrochemical measurement based exclusively on Cu^I/L and Br-Cu^{II}/L species, whereas stopped flow UV technique follows the change of

the overall Cu^I and Cu^{II} species (including Cu^I and Cu^{II} with or without ligand or halide),.



Figure S3. Determination of K_{ATRP} value of Cu^IBr/Me₆TREN in pure DMSO with MBrP as the initiator (a) the evolution of Cu^{II} species; and (b) F(*Y*) function vs time at 25 °C.

Possible effect of intramolecular chain transfer

Radical polymerization of acrylates may involve intramolecular chain transfer (backbiting) which could cause the formation of mid-chain (tertiary) radicals. The coefficient of propagation and termination for tertiary radicals can be different from secondary radicals. In ATRP, the tertiary radical can be deactivated to tertiary alkyl halide, which has different K_{ATRP} value. The rate of backbiting reaction is relatively slow. As a consequence, the influence of the tertiary alkyl halides and radicals on the K_{ATRP} values is small.

The radical concentration calculated from the experiment corresponds to the concentration of secondary radicals. The propagation rate coefficient of tertiary radicals is 10³ times smaller than that of secondary radicals.⁹ Even if the concentration of tertiary radicals could be relatively high, the consumption of monomer is mainly caused by secondary radicals.

The concentration of tertiary alkyl halide is much lower than that of secondary alkyl halide because

the backbiting reaction rate coefficient is slow.¹⁰ Tertiary radicals are generated by the backbiting reaction with a rate coefficient of $k_{bb} = 1.4 \times 10^2 \text{ s}^{-1}$ at 25 °C for butyl acrylate (BA).⁹ The tertiary alkyl halide as the dormant species is formed by deactivation of a tertiary radical with X-Cu^{II}/L. Each propagation reaction converts the tertiary radical to secondary radical. Termination reactions also consume the tertiary radicals. By considering the formation of tertiary structures and ignoring its consumption, the maximum possible concentration of tertiary radicals ([P_n-X₁]) can be calculated as:

$$([\mathbf{P}_{nt}] + [\mathbf{P}_{n} - \mathbf{X}_{t}])_{upper} = k_{bb} [\mathbf{P}_{ns}] t$$
(S2)

For example, in the polymerization system described in entry 3, Table S2, the concentration of secondary radical ($[P_{ns}]$) is 6×10^{-10} M. The maximum concentration of tertiary species formed in 2 h is 0.6 mM which represents only 2% of the total dormant species ($[EBrP]_0$). Under conditions, presented in entry 10 Table S2, the maximum concentration of tertiary structures is 1.2 mM after 0.5 h which equals to 4% of $[EBrP]_0$. The concentration of tertiary species could be even lower, due to the reactions which can consume tertiary radicals.

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