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Ring opening polymerisation of L-lactide initiated by oxyethyl methacrylate–aluminium trialkoxides Part 2. End groups exchange

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Abstract

The side reactions in the synthesis of oxyethylmethacrylate-functionalised poly(L-lactide) macromonomers using aluminium mono- and trialkoxides carrying this functionality have been studied. In addition to the expected changes in the final molecular weight for this kind of polymerisations, changes in the structure of the chain end-groups have been identified by spectroscopic techniques. Radical polymerisation of the functionalised macromonomers has also been detected, especially when dealing with low molecular weight prepolymers.

Keywords: Poly(L-lactide); Aluminium alkoxides; Side reactions

1. Introduction

Regarding the polymerisation of lactones and lactides, special attention has been paid to aluminium derivatives and particularly to aluminium alkoxides, as they have been proved to be effective promoters of the ring opening polymerisation of such monomers. The coordination–insertion mechanism leads to a polymerisation where the molecular weight and the chemical nature of the chain end functional groups can be controlled, and no side reactions take place under appropriate experimental conditions [1–4].

This mechanism has been well documented by excellent works of Jérome et al. [5–10], and offers an interesting way for the preparation of macromonomers of controlled functionality and molecular weight, as well as very low polydispersity. Moreover, the strategic initiation of the ROP of lactones and lactides with HEMA-functionalised aluminium alkoxides, and the control of the termination step by acryloyl or methacryloyl chloride, allows the preparation of α,ω-dimethacryloyl derivatives of poly(lactide) (PLA) or poly(ε-caprolactone) (PCL). In this sense, Jérome et al. [10], in a recent publication, describe the preparation of bioerodible and biocompatible amphiphilic networks based on tailored PLA and PCL dimacromonomers.

It is well known that ionic chain ends in anionic and cationic polymerisation of lactones cause transesterification reactions even at moderate temperatures [11,12]. Intramolecular transesterification reactions ("back-biting") are responsible for degradation and cyclic oligomers formation; intermolecular transesterification reactions modify the sequences in copolylactones and prevent the formation of block copolymers. Both kind of secondary reactions are responsible for the broadening of the molecular weight distribution.

All these processes have been described in ionic polymerisations of lactones, and although there is less information concerning the transesterification activity of covalent metal alkoxides, it has been seen that under certain reaction conditions they promote the degradation by intramolecular transesterification reactions. It is known that some covalent metal alkoxides like titanium or zirconium propoxides are good transesterification catalysts under the conditions employed in the production of polyesters like PET and related copolyesters; however, the reaction temperatures used in these condensation processes are in the range 250–350°C, which do not provide a real information of their catalytic activity at temperatures between 50 and 150°C, the range in which most of the polymerisation reactions of lactones are carried out.

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Kricheldorf [13] established the following reactivity order in relation to the transesterificating activity of some metal alkoxides:

$$Al(O^iPr)_3 < Zr(O^nPr) < Ti(O^nBu)_4 < Bu_3SnOMe < Bu_2Sn(OMe)_2$$

Jérome et al. [14] have considered the transesterification reactions during the ROP of L-lactide in bulk initiated by $Sn(Oct)_2$ and the beneficial effects of specific additives like triphenylphosphine $P(\phi)_3$, to delay and reduce the back-biting reactions when a stoichiometric ratio of $Sn(OCt)_2$ and $P(\phi)_3$ is used as catalyst, but the role of $P(\phi)_3$ in this kind of reactions has to be clarified considering that the catalytic behaviour in the ROP is still under debate.

Kasperczyk et al. [15] compare the activity of initiators containing aluminium or zinc in the copolymerisation reaction of L-lactide and ε-caprolactone, and they conclude that the initiators containing zinc are more efficient transesterificating agents than those containing aluminium. In fact, as it is demonstrated by the results obtained in this work and others [3,8], under certain reaction conditions, the polymerisation of lactides initiated by aluminium alkoxides, functionalised or not, is living and provides products of predictable molecular weight and narrow molecular weight distribution, which indicates the absence of secondary transesterification reactions. However, this is true as far as the reaction does not exceed the time required to reach high conversions and/or it is carried out at an excessively high temperature.

In addition to transesterification reactions, Jérome et al. [9] have described other secondary reactions in the ROP of lactide initiated by HEMA aluminium mono-alkoxides. They find experimental evidences of free radical polymerisation of the functionalysed macromonomers at moderate temperatures (70°C) when the monomer/initiator molar ratio is small (<10).

In the present work, we have considered the ROP of L-lactide initiated by tri-HEMA functionalised aluminium alkoxide, taking into consideration that the kinetic behaviour [16] in the polymerisation is different when tri-HEMA-functionalised alkoxides are used instead of mono-HEMA alkoxides (i.e. the rate of polymerisation is at least 5 times higher for tri-HEMA alkoxides respect to mono-HEMA alkoxides). The behaviour of this polymerisation is described considering the exchange reactions with the participation of the acrylic derivative, as well as the transesterification processes observed during the polymerisation in different experimental conditions.

2. Experimental

L- and DL-Lactides were prepared by catalytic thermolysis of poly(L-lactic acid) or poly(DL-lactic acid) oligomers in the presence of zinc oxide. They were purified by recrystallisation (3 times) from dry ethyl acetate and dried for 24 h at 25°C under reduced pressure before polymerisation.

Triethyl aluminium, 1 M solution in hexane (Aldrich) was diluted in dry toluene. Aluminium isopropoxide (Fluka) was distilled under vacuum and dissolved in dry toluene. The solution concentration of both aluminium derivatives was determined by complexometric titration of Al by EDTA.

2-Hydroxyethyl methacrylate (HEMA) of high purity, containing less than 0.5% of ethylene glycol dimethacrylate was dried over molecular sieves (4 Å) and distilled before use. Triethylene glycol dimethacrylate (Fluka) was treated in the same manner.

3-*tert*-Butyl-4-hydroxy-5-methyl-phenyl-sulfide (Aldrich) was dried by azeotropic distillation with dry toluene (3 times).

Toluene and ethyl acetate were dried by refluxing over CaH_2 and $CaCl_2$, respectively, and distilled under nitrogen atmosphere just before use.

Polymerisations were carried out with stirring, in toluene solution, in an exhaustively flamed and nitrogen-purged glass reactor. The monomer was first charged into the reactor in a glove box under nitrogen atmosphere. Then solvent was added through rubber septa with syringes and stainless steel capillaries. The initiator was synthesised in situ, adding the required amounts of triethyl aluminium and HEMA. The reaction mixture was kept at room temperature for 3 h and at 40°C for 30 min. Then the temperature was raised to the desired polymerisation temperature. At various time intervals several samples were taken out via syringe. These aliquots were treated with dilute HCl in order to stop the reaction and extract the initiator residues. The reaction mixture was washed with water to neutral pH, dried with anhydrous $MgSO_4$ and finally concentrated for NMR and GPC analysis.

^1H and ^{13}C NMR spectra were recorded in deuterated chloroform solution with a Varian VXR-300 spectrometer at 25°C.

Molecular weight and molecular weight distribution were determined by using side exclusion chromatography SEC, (Waters 150-C ALC/GPC) operating at 25 or 30°C in chloroform or THF and calibrated with polystyrene standards. The universal calibration method was applied for poly(L-lactide) on the basis of the following viscosimetric relationships, valid in chloroform at 25°C:

$$[\mu] = 11.2 \times 10^{-5} M_n^{0.73} (PS)$$

and

$$[\mu] = 7.4 \times 10^{-5} M_n^{0.87} (PLLA)$$

For poly(DL-lactide), the following viscosimetric relationships, valid in THF at 30°C, were used:

$$[\mu] = 1.25 \times 10^{-2} M_n^{0.717} (PS)$$

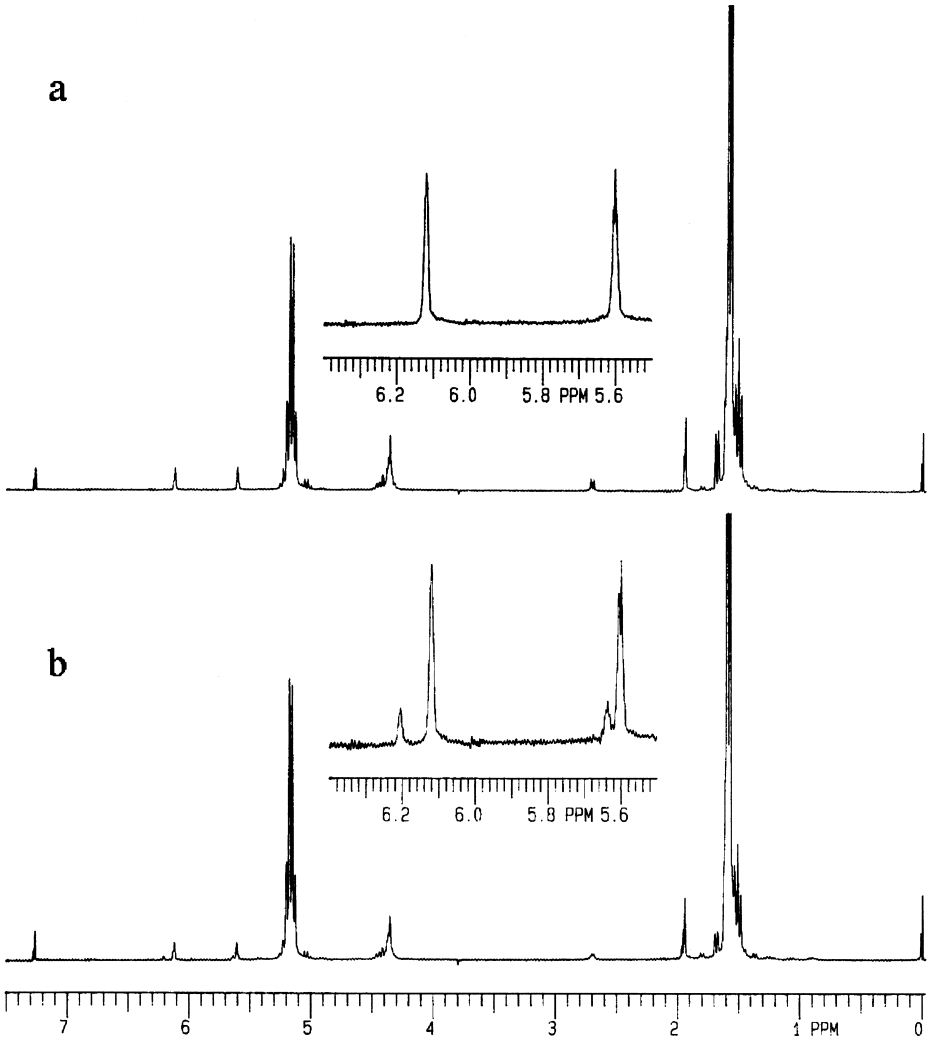


Fig. 1. Change of the ^{1}H NMR spectra of samples of HEMA-functionalised poly(L-lactide) macromonomer extracted at different reaction times. $[LA]_0/[Al] = 31.2$; $M_{n\ theor.} = 1600$. $T = 80°C$: (a) 5 h; (b) 160 h.

and

$$[\mu] = 5.49 \times 10^{-2} M_n^{0.639} (\text{PDLA})$$

3. Results and discussion

In order to study the influence of each reaction variables on these side reactions, several polymerisations of L-lactide were carried out at 60 and 80°C for three theoretical molecular weights, $M_n = 1600$, 3100 and 9100. Samples taken at different reaction times were analysed by GPC and ^{1}H and ^{13}C NMR spectroscopy.

In agreement with previous studies [5–8], the results indicate that at final conversion, the molecular weights correspond to the expected values based on the initial $[M]_0/[Al]$ ratio, and the corresponding molecular weight distributions are narrow, between 1.1 and 1.3. However, any increase of the reaction time leads to the broadening of the molecular weight distribution as a consequence of transesterification reactions, this effect being more noticeable as the molecular weight considered is lower. In addition, an increase of the molecular weight is also observed, above the expected theoretical molecular weight, this also being more evident for lower molecular weight macromonomers.

The analysis of the ^{1}H NMR spectra shows that the area corresponding to the methacrylic protons decreases with respect to that of the methine proton of the polyester chain which means that the methacrylic double bond polymerises thermally. As it was demonstrated by Jérome et al. [14], during the synthesis at 70°C of oxyethyl methacrylate-functionalised poly(DL-lactide) macromonomers, radical homopolymerisation can take place when dealing with very low molecular weight macromonomers ($M_n < 1000$). The high molecular weight products isolated in their work ($M_n > 200\,000$) were not detected in our study neither by new ^{1}H NMR signals corresponding to the poly(macromonomer) nor by their GPC traces. This agrees with a low

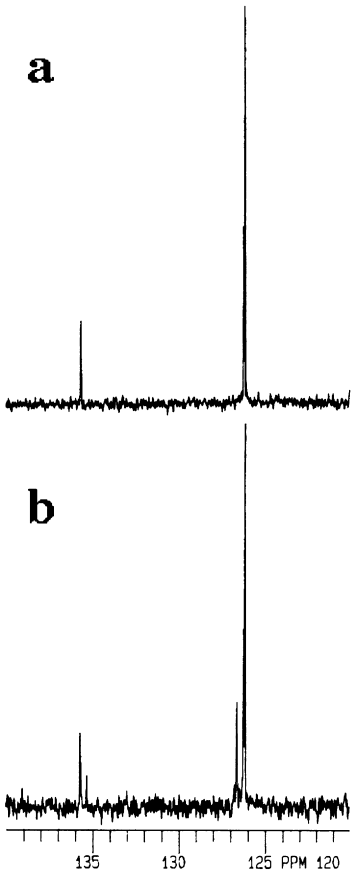


Fig. 2. Change of the ^{13}C NMR spectra of samples of HEMA-functionalised poly(L-lactide) macromonomer extracted at different reaction times. $[LA]_0/[Al] = 31.2$, $M_{n\ theor.} = 1600$,. $T = 80°C$: (a) 5 h; (b) 160 h.

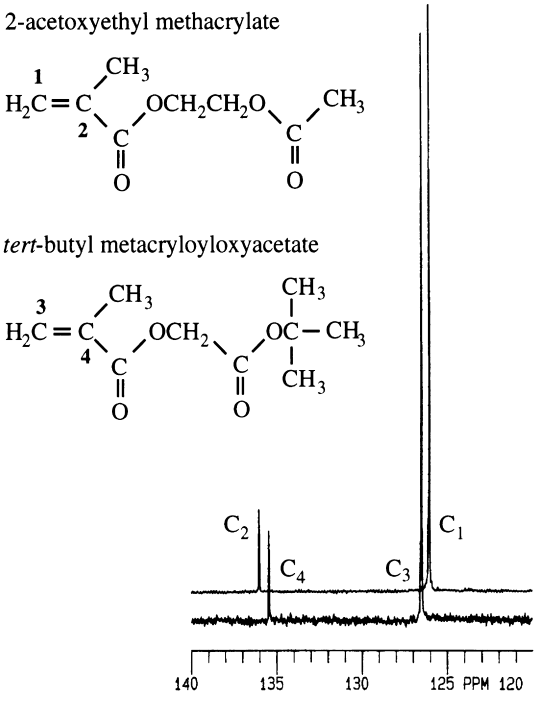


Fig. 3. ^{13}C NMR spectra (in the methacrylic double bond region) of 2-acetoxyethyl methacrylate and *tert*-butyl metacryloyloxyacetate.

degree of polymerisation and low conversion of radical polymerisation, probably due to the fact that the macromonomers in our study have a higher molecular weight ($M_n > 1600$) in comparison to those in Jérome's work ($M_n < 1000$).

The polymerisation of *rac*-DL-lactide was also studied using the same trialkoxides and under similar polymerisation conditions in order to evaluate the transesterification activity of these initiators by means of the effect on sequence distribution.

Bero et al. [17] have described the ^{13}C NMR signals of the methine carbon in terms of sequences as long as hexads. However, in view of the resolution of the corresponding signals in our spectra, we consider that, for quantitative evaluations, an estimate of tetrads gives higher accuracy and allows the analysis in terms of the so-called "transesterification coefficient" *T*, defined by them as

$$T = I_{ssi}/I_{max}$$

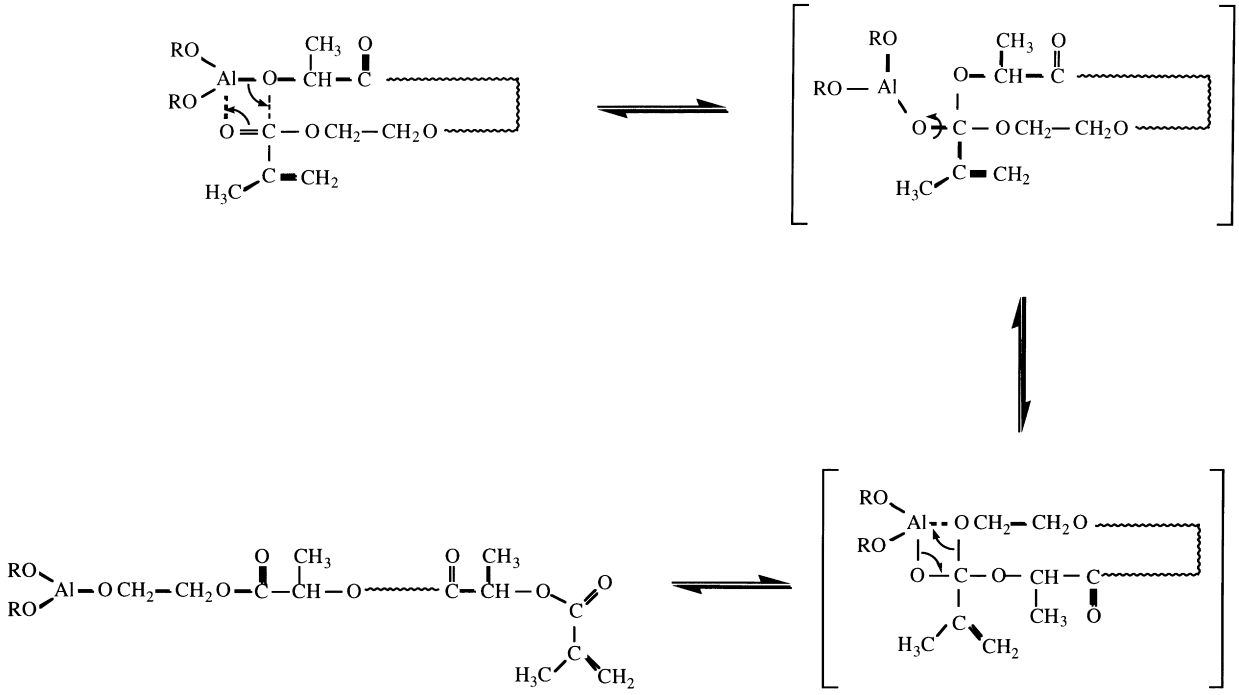
where I_{ssi} is the intensity of ssi tetrad, and I_{max} is the maximum intensity of ssi tetrad in the single-addition Bernoullian statistics ($I_{max} = 0.125$).

Thus, for the synthesis at 80°C of a macromonomer with final $M_n = 3100$, the effect of interchange reactions is low at relatively short reaction time (6 h, conversion <90%), but increases noticeably with reaction time up to a value of $T =$ 58% for a long reaction period of 130 h.

Transesterification reactions during the synthesis of HEMA-functionalised poly(L-lactide) macromonomers not only have an important effect on molecular weight distribution. In fact, the analysis of their ^1H and ^{13}C NMR spectra reveals an interesting change in the chemical nature of the methacrylic double bond. Fig. 1 shows the ^1H NMR spectrum of a macromonomer (theoretical molecular weight $M_n = 1630$) extracted from the reaction medium after 5 h at 80°C and after 160 h. The double bond protons region of the second spectrum clearly shows two additional signals at 5.64 and 6.20 ppm which were absent in the first one. If we consider the model compound that reproduces the methacrylic end of the polylactide chain, 2-acetoxyethyl methacrylate, the new signals appearing in the macromonomer ^1H NMR spectrum should correspond to a similar structure where new chemical groups induce a more deshielding effect on the methacrylic double bond protons. After the analysis of the spectrum of another methacrylic compound in which this effect had been seen, *tert*-butyl metacryloiloxyacetate, it can be supposed that the new structure must be very similar to this second model compound, and considering the chemical groups present in the macromonomer chain, the following structure could be proposed:

$$CH_2 = C(CH_3)–COO–CH(CH_3)–COOR$$

Similar differences are observed when the ^{13}C NMR spectra of macromonomers and both model compounds are analysed: Fig. 2 shows the macromonomer ^{13}C NMR spectra after 5 and 160 h; Fig. 3 compares the ^{13}C NMR spectra



Scheme 1.

of the model compounds mentioned above. As can be seen, the different chemical shifts are in perfect agreement with the signals of the macromonomer treated for long reaction times which corroborates the formation of the proposed structure.

The intensity of those new signals increases with reaction time and temperature which means that their formation could be directly correlated with transesterification reactions. In fact, the proposed new structure is feasible if we consider a transesterification reaction of the methacrylic carbonyl. Scheme 1 shows a tentative mechanism that could explain the origin of such an structure.

The proposed mechanism is based on an intramolecular transesterification reaction (*back-biting*) but an *inter*molecular mechanism would also lead to the same structure. The way that concentration and macromonomer molecular weight influence the final result supports the idea that both mechanisms must be present. Thus, Fig. 4 represents the change with reaction time (counted after at least 90% conversion was reached) of the area of one of the new

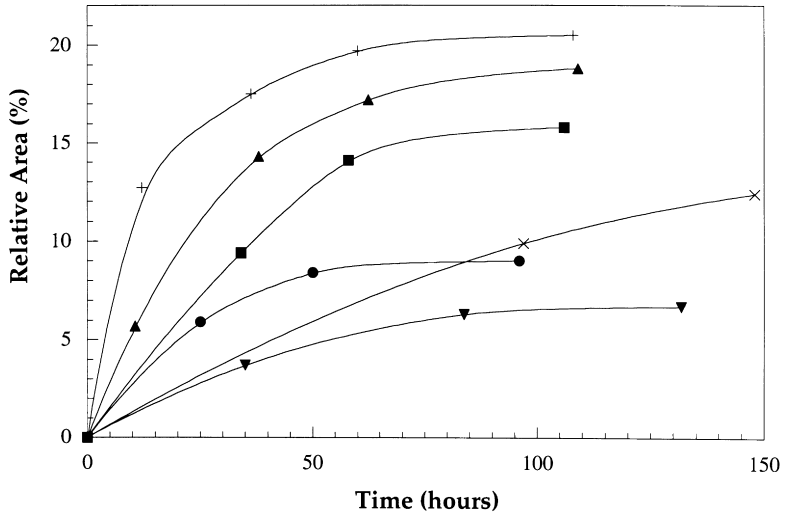


Fig. 4. Change in the relative area of the new signals with reaction time: (●) $M_{n\ theor.} = 3100$, $T = 80°C$, Trialkoxide, $[LA]_0 = 0.2$ mol/l; (■) $M_{n\ theor.} = 3100$, $T = 80°C$, Trialkoxide, $[LA]_0 = 0.5$ mol/l; (▲) $M_{n\ theor.} = 3100$, $T = 80°C$, Trialkoxide, $[LA]_0 = 1.5$ mol/l; (▼) $M_{n\ theor.} = 3100$, $T = 80°C$, Monoalkoxide, $[LA]_0 = 0.5$ mol/l; (+) $M_{n\ theor.} = 1600$, $T = 80°C$ Trialkoxide, $[LA]_0 = 0.5$ mol/l; (▼) $M_{n\ theor.} = 3100$, $T = 60°C$, Trialkoxide, $[LA]_0 = 0.5$ mol/l.

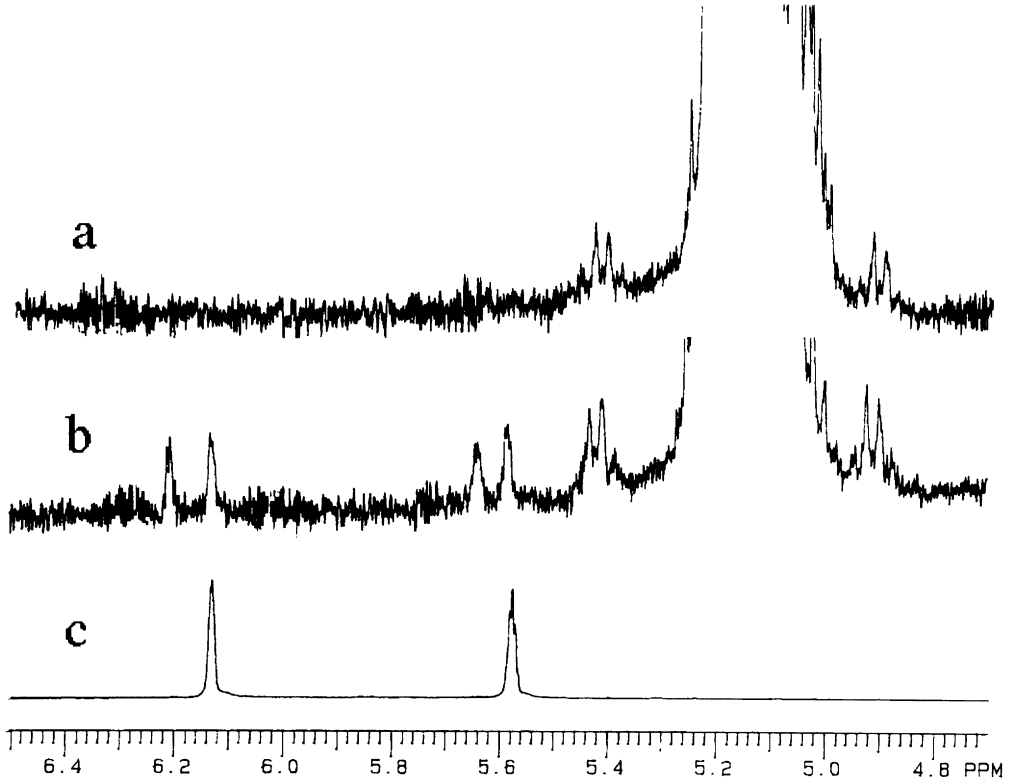


Fig. 5. (a) ^{1}H NMR spectrum of poly(L-lactide) obtained in the polymerisation of L-lactide initiated by aluminium isopropoxide at 80°C; $M_{n\ theor.} = 3100$. (b) ^{1}H NMR spectrum of poly(L-lactide) obtained under the same reaction conditions but 72 h after the addition of triethyleneglycol dimethacrylate (dimethacrylate/isopropoxide groups molar ratio 5/1). (c) ^{1}H NMR spectrum of triethylenglycol dimethacrylate.

signals in relation to the total area (relative area $= A_1/(A_1 + A_2) \times 100$, where A_1 is the area corresponding to the signal at 6.20 ppm and A_2 that at 6.12 ppm) as a function of several reaction parameters. If we consider the effect of monomer concentration ((●), (■), (▲)) it is easy to deduce from this figure, the presence of *inter*molecular reactions, as transesterification reactions are favoured at higher concentrations. Concerning the effect of temperature ((×), (▼)) and molecular weight ((×), (+)), it can be observed that secondary reactions on the methacrylic carbonyl not only are favoured at higher temperatures but also at lower $[LA]_0/[Al]$ ratios, that is, for low-molecular weight macromonomers. Logically an increase of the concentration of active centres accounts for this result; thus, if we compare the results obtained in the polymerisation with $[LA]_0 = 1.5$ mol/l and $M_n = 3100$ (▲), with those in the case of $[LA]_0 = 0.5$ mol/l and $M_n = 1600$ (+), even though the $[LA]_0/[Al]$ ratio in the first case is twice higher than in the second one the effect on the methacrylic unit is very similar, due to the increase of the active centres concentration (1.5 times higher).

In relation to the influence that could have the degree of substitution of the aluminium alkoxide, that is, mono- or trialkoxide ((×) or (■)), in sight of the results reflected in Fig. 4 it can be said that the trisubstituted initiator seems to have a higher activity. This enhanced activity must be related with the increased ionic character of the Al–O bond when it is surrounded by three electron-donating alkoxide groups [16]. In agreement with this, it is also observed that the broadening of the molecular weight distribution is more noticeable when the trialkoxide is used.

Finally, we have seen that the addition of a methacrylic compound to a living polymerisation of L-lactide initiated by aluminium triisopropoxide leads to similar phenomena, resulting from interchange reactions between this compound and the propagating chain end. Thus, to a living polymerisation of L-lactide initiated by aluminium triisopropoxide, triethylenglycol dimethacrylate was added, once most of the L-lactide had polymerised. Fig. 5 shows the methacrylic region of ^{1}H NMR spectra corresponding to samples withdrawn at different reaction times: (a) poly(L-lactide) ($M_n = 3500$) spectrum just before the addition of the methacrylic compound; (b) a sample of poly(L-lactide) extracted 72 h after the addition of the methacrylate; and (c) the added methacrylic compound. It is clear in the second spectrum that, along with the signals of the methacrylate that has not been completely removed, two new signals can be distinguished. Their chemical shifts perfectly agree with those of the new structure that resulted from the transesterification reactions on the synthesis of HEMA-functionalised poly(L-lactide) macromonomers. Consequently these

new signals are expected to be generated by an interchange reaction between the carbonyl group of the dimethacrylate and the living polylactide chain end.

To conclude, it is necessary to stress that the transesterification reaction is produced also with the participation of inner LA units of the polymeric backbone, being the process statistic. When the transesterification reaction is produced with inner LA units, there is not any structural change in the methacrylic unit. Assuming that there is not a preferential interaction with the methacrylic chain end moiety, the statistic nature of the overall process would justify the fact that the end-group exchange only proceeds to a certain degree (depending on the experimental conditions) and then levels off.

4. Conclusions

The polymerisation of L-lactide using HEMA-functionalised aluminium alkoxides can lead to two side reactions when the reaction exceeds the time required to reach high conversions. These are transesterification reactions and radical polymerisation of the methacrylic double bond. As a consequence, the measured molecular weights do not correspond to the expected value on the basis of the [monomer]/[initiator] molar ratio. It must be pointed out that the contribution of the radical homopolymerisation of the macromonomer does not seem to be remarkable because of the low polymerisation degree reached. The "backbiting" reactions are responsible not only for the changes in molecular weight, but also of the modification of the chemical structure of the methacrylic functionality attached to the aluminium alkoxide.

Acknowledgements

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References

[1] Dubois Ph, Jérome R, Teyssié Ph. Makromol Chem, Macromol Symp 1991;42/43:103.
[2] Dubois Ph, Jérome R, Teyssié Ph. Polym Bull 1989;22:475.
[3] Barakat I, Dubois Ph, Jérome R, Teyssié Ph. J Polym Sci: Polym Chem 1993;31:505.
[4] Eguiburu JL, Fernandez-Berridi MJ, San Román J. Polymer 1995; 36(1):173.
[5] Dubois Ph, Jacobs C, Jérome R, Teyssié Ph. Macromolecules 1991;24:2266.
[6] Dubois Ph, Jérome R, Teyssié Ph. Macromolecules 1991;24:977.
[7] Barakat I, Dubois Ph, Jérome R, Teyssié Ph, Goethals E. J Polym Sci: Polym Chem 1994;32:2099.
[8] Dubois Ph, Jacobs C, Jérome R, Teyssié Ph. Macromolecules 1991;24:2266.
[9] Barakat I, Dubois Ph, Grandfils Ch, Jérome R. J Polym Sci Polym Chem 1996;34:497.
[10] Barakat I, Dubois Ph, Grandfils C, Jérome R. J Polym Sci A: Polym Chem 1999;37:2401.
[11] Kricheldorf HR, Jonté JM, Dunsing R. Makromol Chem 1986; 187:1611.
[12] Sosnowski S, Slomkowski S, Penczek S. J Macromol Sci Chem 1983;20:979.
[13] Kricheldorf HR, Berl M, Scharnagl N. Macromolecules 1988;21:286.
[14] Degée Ph, Dubois Ph, Jacobsen S, Fritz HG, Jérome R. J Polym Sci A: Polym Chem 1999;37:2413.
[15] Kasperczyk J, Bero M. Makromol Chem 1993;194:913.
[16] Eguiburu JL, Fernández-Berridi MJ, Cossío FP, San Román J. Macromolecules 1999;32:8252.
[17] Bero M, Kasperczyk J, Jedlinski Z. J Makromol Chem 1990; 191:2287.