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New isocyanates from amino acids

W. Hettrich* and R. Becker
Institut für Angewandte Chemie e.V., Rudower Chaussee 5, D-12489 Berlin-Adlershof, Germany
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New di- and polyisocyanates were synthesized from α-amino acids. The reaction route included the preparation of α-isocyanatoacyl chlorides from the corresponding amino acids and trichloromethyl chloroformate and their conversion into diisocyanato diesters by reaction with silylated alcohols. For comparison, 3-isocyanatopropanoyl chloride was also prepared by reaction of the *O*-silylated β-alanine with 4,4′-methylene bis(phenylisocyanate) and subsequent conversion of the isocyanatosilyl ester with thionyl chloride. Ethanediol, the isomeric propanediols, 1,4-butanediol, 1,6-hexanediol and glycerol were the alcohol components. The amino acids glycine, L- and DL-α-alanine, L-leucine, and L-phenylalanine were investigated. Some polyurethanes made from the isocyanates and several polyols were characterized by mechanical testing and thermomechanical analysis. The degradation behaviour was evaluated as a preliminary investigation. The new monomers may be useful candidates for the preparation of degradable polyurethanes for medical applications. © 1997 Elsevier Science Ltd.

(Keywords: isocyanates; amino acids; polyurethanes)

INTRODUCTION

Polyurethanes are the most used polymers in the special field of implantable biomaterials[1–3] due to their extraordinary biocompatibility and their exceptional mechanical properties. They are used especially in long-term devices[4]. In the field of degradable materials one can find only a few reported attempts to prepare products based on polyurethanes[5,6]. In recent years, however, the aforementioned polymer class has been under critical evaluation because the common aromatic or aliphatic isocyanates such as 4,4′-methylene bis(phenylisocyanate) (MDI), 1,6-hexamethylene diisocyanate (HDI) and 4,4′-methylene bis(cyclohexylisocyanate) (H_{12}MDI) may lead to toxic metabolites during polymer hydrolysis[7,8]. Therefore, there is a real demand for new isocyanates for both long-term stable and degradable polyurethanes.

The aim of this investigation is to develop such isocyanates as reactants in biodegradable and bioresorbable polyurethanes without potential toxic metabolites[9]. The conversion of amino acids into NCO-group-bearing materials that allow classic polyaddition has been discussed in the literature for some years as a promising way to prepare biodegradable polyurethanes. The few investigations of this synthetic problem are all based on ethyl 2,6-diisocyanatohexanoate[10–13]. We intend to use easy synthetic procedures and simple mono-amino acids to synthesize appropriate diisocyanates.

EXPERIMENTAL

Materials

The amino acids, lactic acid, hexamethyl disilazane (HMDS) (Fluka, purum or better), trichloromethyl chloroformate (TCF) (Fluka, pract.) were used as received. The diols and polyols (Aldrich) were distilled or dried by means of a rotating evaporator under reduced pressure and stored over molecular sieve 4 A. Dioxan (Fluka) was refluxed in the presence of calcium hydride and distilled directly into the reaction flask.

Synthesis

3-Isocyanatopropanoyl chloride (7) from 3-aminopropanoic acid (8) (IV, R = $(CH_2)_2$) via transisocyanatization (Figure 2, *route B*).

(A) Trimethylsilyl 3-aminopropanoate (9) (V, R = $(CH_2)_2$). In a 250 ml three-necked flame-dried flask equipped with a magnetic stirrer, thermometer, reflux condenser and gas inlet, 0.2 mol (17.81 g) of 3-aminopropanoic acid (**8**) and 0.12 mol of HMDS (25.0 ml) containing 0.5 mol% (0.18 g) saccharin with respect to amino acid (catalyst) were mixed with 100 ml of toluene under a slow stream of argon. The mixture was then refluxed for 18 h until no more ammonia was formed. The reflux condenser was replaced by a distillation head wrapped with a strip heater adjusted to a temperature of 50°C. After removing the solvent at 10 kPa the cloudy residue was distilled under reduced pressure, giving 27.4 g (85%) of trimethylsilyl 3-aminopropanoate (**9**). B.p.: 55–60°C (0.013 kPa). Calculated for $C_6H_{15}NO_2Si$ (%)—C 44.68, H 9.37, N 8.68, Si, 17.41; found (%)—C 45.04, H 9.43, N 8.60, Si 17.38. I.r.: 1252 and 842 cm^{-1} ($(CH_3)_3SiO$).

(B) Trimethylsilyl 3-isocyanatopropanoate (10) (VI, R = $(CH_2)_2$). A distillation apparatus was charged with 1.0 mol (250 g) of MDI and heated to 90°C under argon and magnetic stirring. Then 0.3 mol (48.3 g) of trimethylsilyl 3-aminopropanoate (**9**) placed in a dropping funnel at a temperature of 60°C was added in one portion to the isocyanate. The mixture was further

* To whom correspondence should be addressed

heated to 150°C on an oil bath. The isocyanato silylester (**10**) distilled after slowly reducing the pressure at this temperature. B.p.: 80°C (0.12 kPa). Yield: 49 g (84%). Calculated for $C_7H_{13}NO_3Si$ (%)—C 44.90, H 7.00, N 7.48, Si 15.00; found (%)—C 45.00, H 7.08, N 7.44, Si 14.92. I.r. 2269 cm^{-1} (NCO); 1247 and 848 cm^{-1} $(CH_3)_3SiO$.

(C) 3-Isocyanatopropanoyl chloride (7). A 0.15 mol (28 g) aliquot of **10** together with 150 ml of toluene were placed in a dry 250 ml three-necked flask equipped with a magnetic stirrer, thermometer, gas inlet, reflux condenser and dropping funnel. The funnel was charged with 0.175 mol (20.8 g) of thionyl chloride. The chloride was slowly added at constant room temperature. The mixture was then refluxed at 80°C for 15 h. After removing the excess of thionyl chloride and the solvent at 10 kPa, **7** distilled at 66–68°C (1.33 kPa). Yield: 11.9 g (84%). I.r.: 2268 (NCO) and 1790 cm^{-1} (COCl). Calculated for $C_4H_4ClNO_2$ (%)—N 10.48; found (%)—N 10.13.

α-Isocyanatoacyl chlorides I (1–6). The syntheses of the α-isocyanatoacyl chlorides were carried out according to Iwakura and co-workers[14,15] with the amino acid hydrochlorides and TCF in 1,4-dioxane. In this way, compounds **1–6** listed in *Table 2* were prepared.

Silylated diols II (11–16) and hydroxyethylamine (17). The alcohols were silylated by refluxing in a small excess of HMDS followed by distillation (substance, b.p., yield: 1,2-bis(trimethylsilyloxyethane) (**11**), 62–63°C (2.3 kPa), 97%; 1,2-bis(trimethylsilyloxypropane) (**12**), 68°C (2.5 kPa), 96%; 1,3-bis(trimethylsilyloxypropane) (**13**), 74°C (2.3 kPa), 96%; 1,4-bis(trimethylsilyloxybutane) (**14**), 98°C (2.7 kPa), 94%; 1,6-bis(trimethylsilyoxyhexane) (**15**), 122°C (2.0 kPa), 92%; 1,2,3-tris(trimethyl-silyloxypropane) (**16**), 110–112°C (2.7 kPa), 99%; *O,N*-bis(trimethylsilyl hydroxyethylamine) (**17**), 120°C (3.6 kPa), 92%).

The lactide triol **18** was prepared from DL-lactic acid and glycerol via the dilactide (molar ratio dilactide/glycerol = 15/1) according to the procedure of Perego *et al.*[16]. Matrix-assisted laser desorption ionization–mass spectrometry (MALDI–MS) analysis: 43 peaks; monomer mass 72; residual mass 19; M_n 1893; M_w 2281.

Alkyl-bis(α-isocyanatoalkanoates) III (19–25). Forty millimoles of the α-isocyanatoacyl chlorides **1–6** and 18 mmol of the silylated alcohols **11–15** were heated to 70–90°C for 20–35 h, while chlorotrimethylsilane was removed at 30–40 kPa. When the silylated glycerol **16** was used, 30 mmol of **1–6** reacted with 9 mmol of **16**. After the reaction finished (disappearance of the chloroformyl group in the i.r. spectra) the crude products were purified by short-path distillation (**19–23**) or by liquid–liquid extraction (**24**). The latter was performed by dispersing 5 g of the crude product in 50 ml of toluene–heptane–mixture (1/9) at 60°C for 5 min in an ultrasonic bath. The cloudy solvent was decanted from the viscous residue. Within 15 min the solvent separated into two phases. After removing the solvent, 0.75 g of **24** was collect from the solvent-rich phase. For analytical data, see *Table 3*.

Polymers. The isocyanato ester **III** and the polyols were mixed at 40°C under argon in the corresponding amounts giving an overall NCO/OH ratio of 1/1. The polymer was degassed, cast as strips (100 × 5 × 2 mm) in a Teflon form and cured at 80°C for 6 h.

Characterization methods

I.r. spectra were recorded on a Perkin Elmer System 2000 FTIR spectrometer. The optical angles of rotation were measured with a Perkin Elmer polarimeter 241. The mechanical measurements were carried out by a Tiratest 2160 instrument, and the thermomechanical measurements by a home-made high-performance equipment (temperature interval −100 to 250°C; load 10 mN). The MALDI–MS spectra were recorded with a Kratos Compact MALDI instrument (matrix: 2,5-dihydroxybenzoic acid). The molecular weights were estimated by gel permeation chromatography (g.p.c.) (Knauer, 3 Jordi columns, tetrahydrofuran eluant, RI-detector, polystyrene calibration). Thin-layer chromatography was also used: sample concentration 1 mg ml^{-1} in (A) aqua destillata (B) buffer solution pH 7.1 and (C) 0.1 M NaCl; temperature 37 and 70°C; Merck cellulose plates; *n*-BuOH/acetone/acetic acid/water = 35/35/7/23 eluant; 5 μl samples were applied; detection λ = 580 nm (ninhydrin); R_f (alanine) = 0.32.

The NCO contents were determined by standard titration using di-*n*-butylamine as the NCO reactant and hydrochloric acid to detect the remaining amine in the presence of bromocresol green as the indicator.

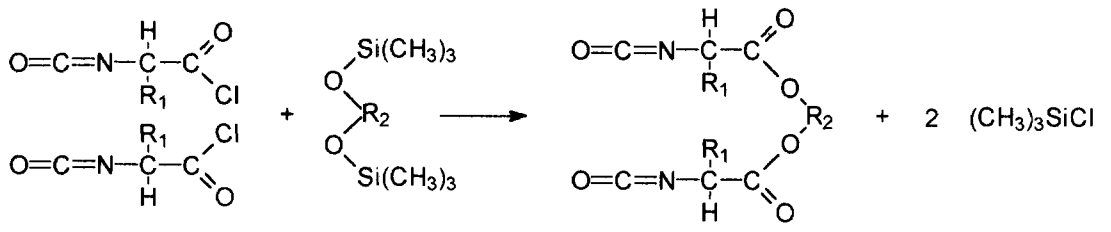
RESULTS AND DISCUSSION

Synthesis of isocyanato esters

We synthesized functionalized mono isocyanato acids from mono-amino acids. We then combined these compounds via the acid functionalities with hydroxy compounds to di- or polyisocyanato compounds. The condensation of α-isocyanatoacyl chlorides (**I**) with silylated alcohols (**II**), according to *Figure 1*, seems to be a suitable route for the preparation of such new mono amino acid-based diisocyanates (**III**). This reaction is possible because the two functional groups of the NCO chlorides differ remarkably in their reactivity. The resulting products are isocyanato esters.

For the preparation of these isocyanatoacyl chlorides, a phosgene-free route was first investigated (*Figure 2*, route **B**) that was originally developed by Mormann and Leukel for amino alcohols and *para-* and *meta*-substituted aromatic amino compounds, respectively[17]. This procedure starts with the silylation of an amino acid (**IV**). The obtained silylester (**V**) can be transformed into the corresponding isocyanato derivative (**VI**) by heating **V** with a large excess of a high-boiling isocyanate as MDI. The reaction proceeds via intermediate urea formation. The product **VI** distils over on further heating the reaction mixture under reduced pressure, during which step the urea is formed from the usually employed MDI. In the last step the isocyanatosilyl ester was chlorinated by thionyl chloride, giving the desired isocyanato chloride (**VII**) without any loss in the NCO function. In the i.r. spectra no NH, NH_2 and CO (from urethane or urea bonds) vibrations were detected, which would result from side products.

In this way we obtained 3-isocyanatopropanoyl chloride (**7**) according to *Figure 2* (route **B**). The yield, however, was lower (*Table 1*, column 5) than the yields



I II III

R_1 = H, CH_3, $CH_2CH(CH_3)_2$, $CH_2C_6H_5$ R_2 = $(CH_2)_2$, $(CH_2)_3$, $CH(CH_3)CH_2$, $(CH_2)_4$, $(CH_2)_6$, $CH_2[CHOSi(CH_3)_3]CH_2$

Figure 1 Condensation of α-isocyanatoacyl chlorides (**I**) with trimethylsilyated alcohols (**II**) to polyisocyanato esters (**III**)

for the phosgenation of β-alanine (*Figure 2*, route **A**; *Table 1*, column 3) reported in the literature. On the other hand, we obtained yields similar to the pure phosgenation route when we used trichloromethyl chloroformate as the co-reactant (*Figure 2*, route **A**; *Table 1*, column 4).

However, this procedure was unsuccessful in the case of α-amino acids (**VIII**) (*Figure 3*). The corresponding silyl esters (**IX**) certainly react in a primary step to form the desired α-isocyanato compounds (**X**), but these are not stable.

We obtained products similar to the mixtures found by Kricheldorf and Greber in attempts to prepare *N*-silylated oxazolidine-2,5-diones (**XI**) by different synthetic methods[18]. They found that the obtained desired product **XI** was in a 1/1 equilibrium with the isomeric α-isocyanato silylester **X** at 0°C (*Figure 3*, route **B**). Since **X** is very reactive towards **XI** above 0°C, both compounds polymerize to an oligomeric product containing anhydride and silylester groups in the chain with increasing temperature. Our product showed at room temperature the same i.r. activities at 1853 and 1785 cm^{-1}, indicating the presence of the anhydride structure (carbonyls of CO(O)OC) as well as the bands at 1724 cm^{-1} (carbonyl vibration of silylester) in addition to the NCO signal at 2296 cm^{-1}. This indicates that a copolymer was formed from **X** and **XI**, according to Kricheldorf[18].

In conclusion, we used a conventional preparation method (*Figure 3*, route **A**), the reaction with TCF, for the synthesis of the α-isocyanatoacyl chlorides (**I**) in a one-step procedure. *Table 2* summarizes the boiling points, the chlorine content, the position of the two characteristic i.r. vibrations (NCO and COCl), and the yields for **1–6**. The angle of optical rotation α is also given for the stereoisomers of alanine.

The yields were sufficiently high in the cases of glycine and the alanines, but for the higher homologues, leucine and phenylalanine, the obtained amounts were small.

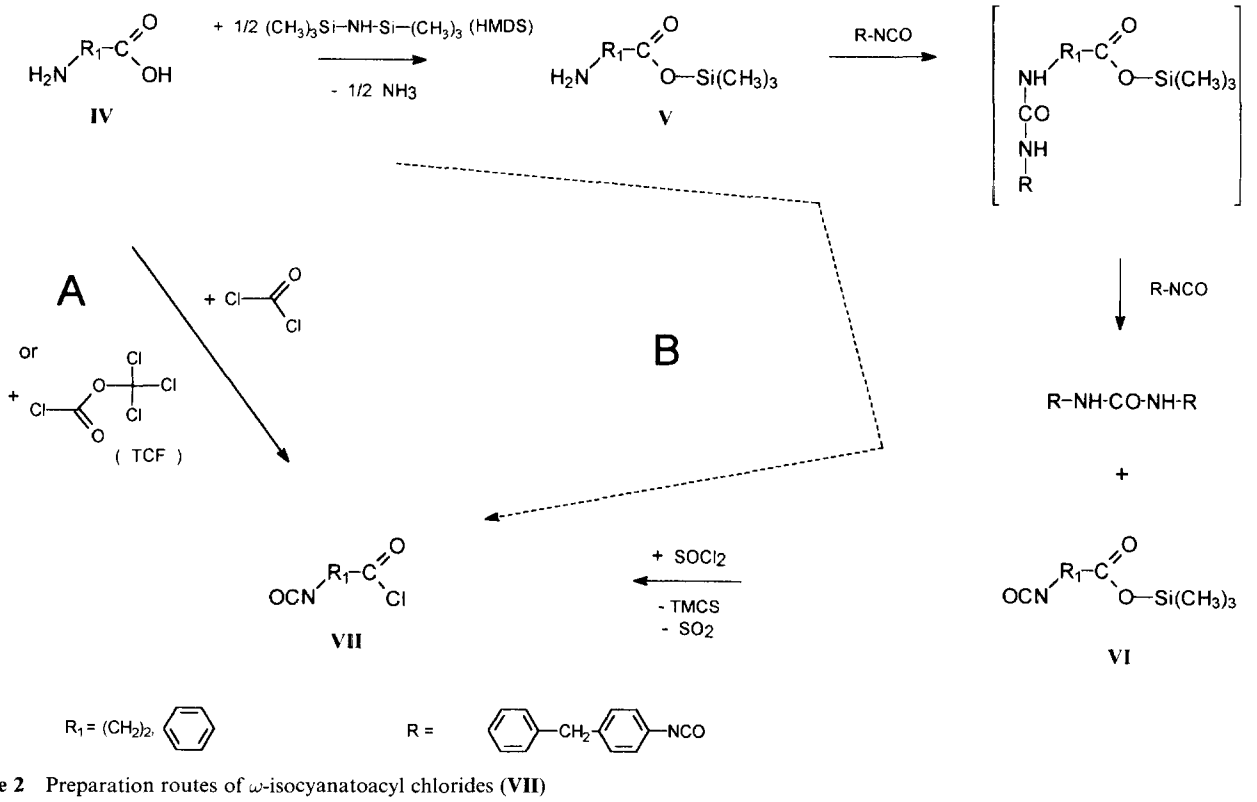


Figure 2 Preparation routes of ω-isocyanatoacyl chlorides (**VII**)

Table 1 3-Isocyanatopropanoyl chloride **VII** (7, $R_1 = (CH_2)_2$) by different preparation methods (*Figure 2*)

	Yield (%) with respect to β-alanine		
B.p. (°C)/kPa	$COCl_2$ [14]	TCF (route A)	Transisocyanatization (route B)
68/1.33	92	85	60

This was mainly caused by decomposition of the isocyanato chlorides of leucine (**5**) and phenylalanine (**6**) during distillation. The purity of the obtained fractions, determined by the chlorine content, was close to the theoretical values.

The reaction between the α-isocyanatoacyl chlorides (**I**) and the silylated alcohols (**II**) to form the isocyanate esters (**III**) (*Figure 1*) was carried out at temperatures between 70 and 90°C and finally under reduced pressure to remove the last traces of the formed chlorotrimethylsilane.

The conversion was controlled by the simultaneous disappearance of the chlorine carbonyl vibration in the i.r. spectrum at about 1790 cm^{-1}, and the formation of the ester carbonyl band around 1740 cm^{-1}. The strong NCO vibration at 2270 cm^{-1} was not influenced during this reaction. The properties of some of the α-isocyanato esters (**19–24**) are summarized in *Table 3*. Compound **25** could only be obtained as a crude product.

Analytical characterizations were performed by i.r. spectroscopy, by elemental analysis, by titrimetric determination of the NCO content and, in some cases, by MALDI–TOF–MS. The esters of glycine and alanine with diols up to six carbon atoms could be distilled, resulting in purities greater than 99%. Both the NCO titration and the determined nitrogen content led to the same result.

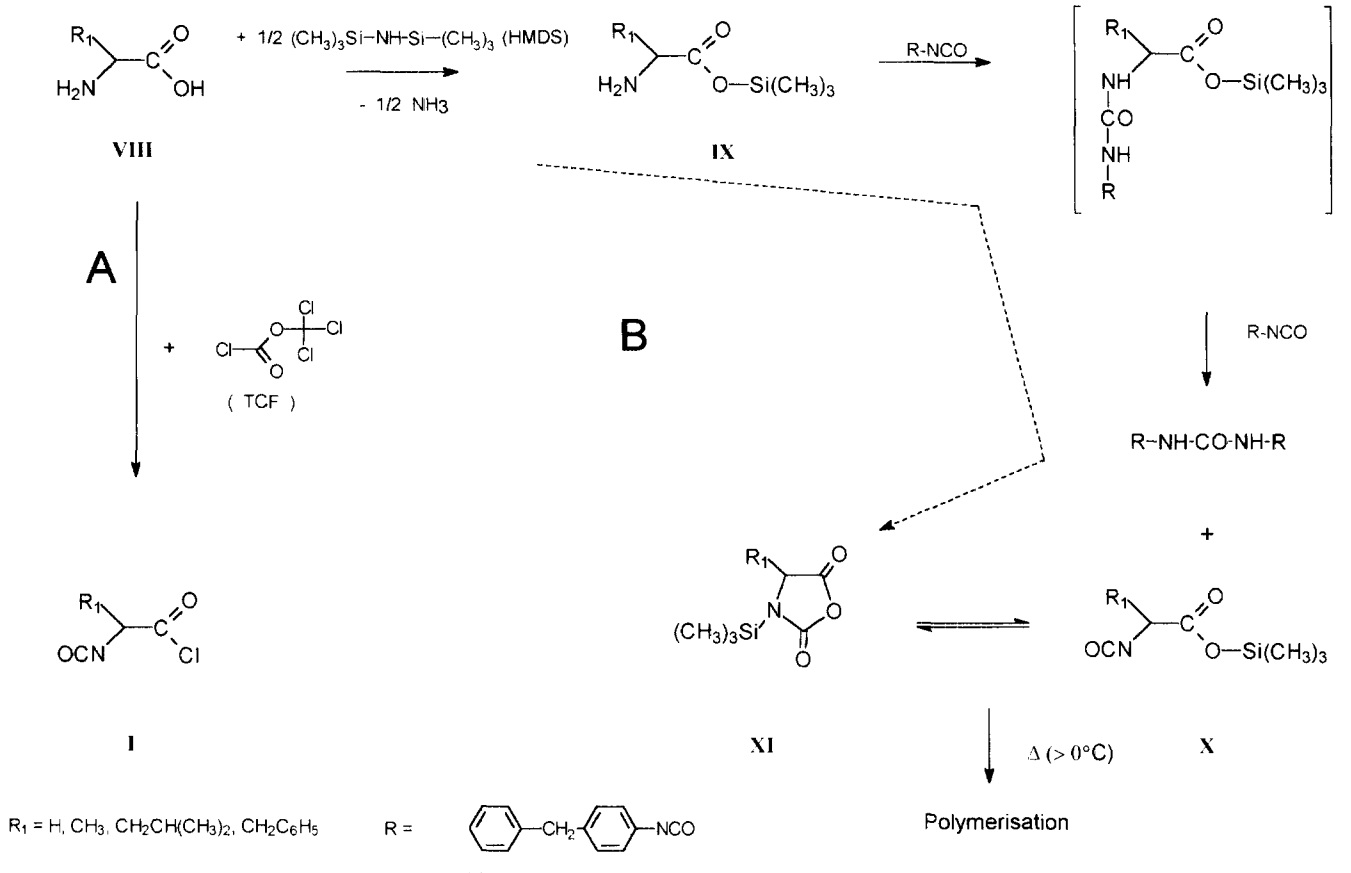


Figure 3 Preparation routes of α-isocyanatoacyl chlorides (**I**)

Table 2 α-Isocyanatoacyl chlorides (**I**) by reaction of the amino acids with TCF (*Figure 3*, route A)

Compounds			Cl (%)				
I	R_1	B.p. (°C)/kPa	Calculated	Found	I.r. (cm^{-1})	[α] (°)[a]	Yield (%)
1	H	64/4	29.70	29.76	NCO 2271, COCl 1789		76
2	DL-CH_3				NCO 2273, COCl 1790		85
3	L-CH_3	67/6.1	26.55	26.80	NCO 2282, COCl 1792	+40.50	79
4	D-CH_3				NCO 2279, COCl 1790	−35.33	77
5	L-$(CH_3)_2CHCH_2$	76/0.9	20.19	20.16	NCO 2275, COCl 1791		18
6	$C_6H_5CH_2$	95/0.03	16.91	16.95	NCO 2273, COCl 1792		2

[a] $[\alpha]_d^{20}$; $c = 1$ (1,4-dioxane)

Table 3 Properties of alkyl bis(α-isocyanato-alkanoates) (**III**)

Compounds **III**	R_1	R_2	B.p.(°C)/kPa	M.p./T_g(°C)	NCO equ., calc./ found	Purity N (%)	Yield (%)	Purification[d]
19	DL-CH_3	$(CH_2)_2$	$117/1.3 \times 10^{-3}$	/5	128.11/127.67	> 99.5	55	A
20	DL-CH_3	$(CH_2)_3$	$117–119/6.7 \times 10^{-4}$	/5	135.12/135.14	99.4	65	A
21	L-CH_3 [a]	$(CH_2)_4$	$138–140/1.3 \times 10^{-4}$	28.4/–	142.14/143.04	> 99.5	56	A
22	DL-CH_3	$CH_2CH(CH_3)$	$124–127/1.3 \times 10^{-3}$	/−5	135.12/136.10	99.3	60	A
23	DL-CH_3	$(CH_2)_6$	$142–146/1.3 \times 10^{-4}$	ND	156.16/157.00	< 99.5	25	A
24	DL-CH_3 [c]	$CH_2CH[O(CO)CH(CH_3)NCO]CH_2$	$160/1.3 \times 10^{-4}$ [b]	/−8	127.77/130.35	98.2	15	B
25	L-$(CH_3)_2CHCH_2$	$(CH_2)_4$	$160/1.3 \times 10^{-4}$ [b]	–	–	–	–	–

ND, not determined
[a] $[\alpha]_D^{20} = +19.94$, $c = 1$ (1,4-dioxan)
[b] Decomposes
[c] Prepared from **2** and glycerol
[d] A, distilled; B, liquid–liquid extraction (toluene/heptane)

The triisocyanate of glycerol (**24**), which is the most serious candidate for a fully natural based bioresorbable polyurethane in this series, could neither be distilled nor crystallized. So we tried a liquid–liquid extraction, leading to a relatively pure product, but in very low yields of about 15%.

Except for the butanediol derivative of L-alanine, having a melting point of 28.4°C (**21**), all the other compounds were obtained as viscous liquids showing only a glass transition in the d.s.c. mode after repeatable heating–cooling cycles.

The distillation of the isocyanato esters strongly improves the purity of the crude products. In the MALDI spectra (not shown) of **21** blocked with methanol, differences between the crude and purified sample were clearly noted. The spectrum of the crude product indicated the presence of some oligomers, probably caused by traces of moisture in the reaction system. The spectrum of the purified isocyanato ester showed a peak with the mass number 372.2 only, corresponding to the molecular weight + H + Na. The results obtained by elemental analyses and the determination of the NCO content fully agree with the MALDI analysis.

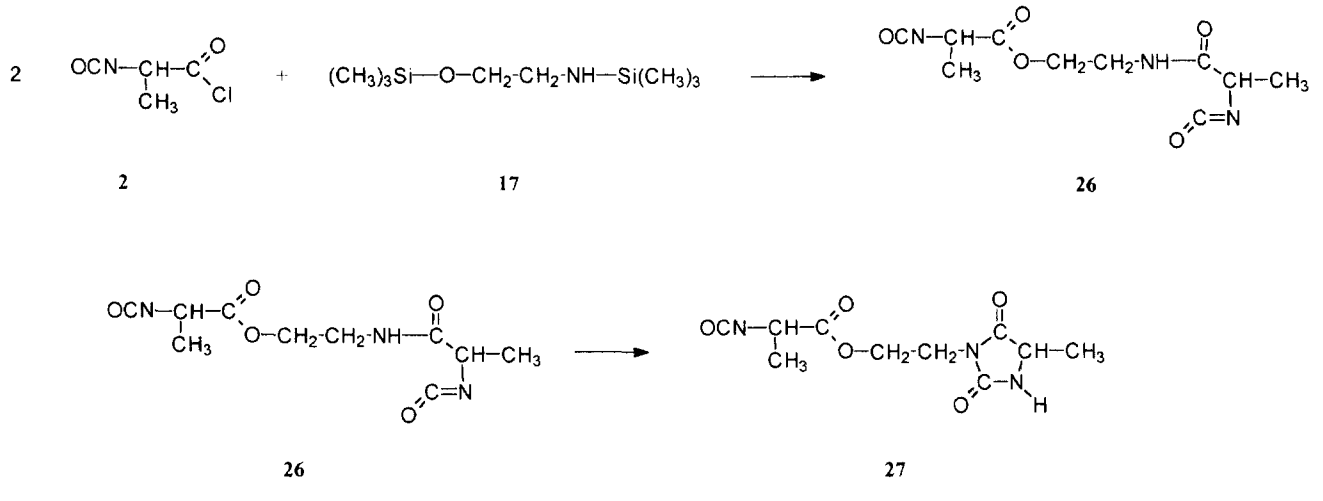
Reactions of the isocyanato chloride **2** with silylated amino compounds, for example silylated hydroxyethylamine (**17**), were also performed to obtain products of higher melting points or at least higher glass transition temperatures (*Figure 4*). Due to the presence of the free hydrogen atom in the formed amide structure, however, we could not get the corresponding diisocyanato species (**26**). The amido group reacts fast with the isocyanato function of the same molecule. The analytical data of the isolated prime fraction indicate a complete formation of the five-membered ring **27**. A corresponding behaviour was found by Mormann *et al.* when they converted equimolar amounts of 3-isocyanatopropanoyl and 4-isocyanatobutanoyl chloride with **17**. The formation of six- and seven-membered rings was found to occur in mixture with the isocyanate[19].

Formation of polymers

The di-α-isocyanato diesters **III** (**19**–**24**) react fast with alcohols commonly used in polyurethane synthesis. In contrast to conventional aliphatic isocyanates one does not need a catalyst to prepare, for example, the polyurethane **28** from 1,4-butanediol and butyl bis-(α-isocyanato-L-propanoate) (**21**) according to *Figure 5* having a molecular weight in the range 6000–15000 (*Table 4*). The absence of any catalyst is very important and valuable for biomedical applications, because all the active urethane catalysts are normally harmful. The reaction is finished after 6 h (disappearance of NCO) under moderate reaction conditions.

The mechanical properties of **28** (*Table 4*), however, are not these of a typical segmented polyurethane. The glass transition temperature of 53°C is relatively low, compared to the melting points of the polyurethanes from butanediol with the β-alanine analogue and MDI, respectively.

Obviously, the α position of the isocyanate leads to a significant softening of the urethane unit. Since this structure is responsible for the formation of the hard segment domains in segmented polyurethanes, one



calcd. for 26 and 27: C, 47.06; H, 5.13; N, 16.46 %

found: C, 47.24; H, 5.27; N, 16.29 %

NCO-equiv. (g/mol): calcd. for 26: 127.62

NCO-equiv. (g/mol): calcd. for 27: 255.23

found: 256.21

Figure 4 Reaction of α-isocyanato-DL-propanoyl chloride (**2**) with *O,N*-bis(trimethylsilyl hydroxyethylamine) (**17**)

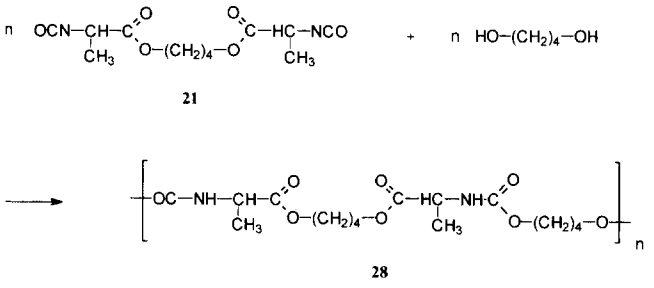


Figure 5 Polymerization of butyl bis(α-isocyanato-L-propanoate) (**21**) with 1,4-butandiol to the polyurethane **28**

cannot find a behaviour comparable to conventional polyurethanes.

After cross-linking of diisocyanato esters (**III**) with a trifunctional alcohol in the presence of a low molecular weight poly(tetramethylene ether)glycol (PTMEG) we obtained the polymers **29–32** with weak elastic properties. The results of thermomechanical measurements of these samples were depicted in *Figures 6a* and *6b*. *Figure 6a* shows the typical plateau of rubber elasticity for the polymers. Only one phase transition could be detected that belongs to the glass transition state of the network more clearly seen in the differentiated thermomechanical plot given in *Figure 6b*. A phase separation into hard and soft segments, i.e. additional peaks in the differentiated thermomechanical plots, was not found. The level of the rubber plateau and the glass transition temperature seem to depend only on the degree of cross-linking. The different diol components in the isocyanato ester do not significantly affect the mechanical properties of the polymer networks.

An exception is the sample based on 1,2-propanediol (**30**). We found a remarkably lower plateau level. This is probably due to the additional methyl group introduced into the urethane unit, as mentioned for polymer **28**.

Table 5 gives the values of some mechanical properties for model polymers **33–35**. Compared are those formed from **21** with different polyols such as PTMEG, glycerol and lactide-triglyceride (**18**). The values of the mechanical properties of these polymers are in the range given for the poly(lactide-*co*-caprolactone) polyol-based materials[9,11]. Similar properties were also obtained by using castor oil (not shown) instead of glycerol.

To estimate approximately the degradation behaviour, a first hydrolysis study using the butandiole urethane of **21** over a period of 3 months was carried out (*Table 6*). The model was stored at 37 and 70°C in water, a sodium chloride solution and a phosphate buffer (samples **36a–e**).

We determined the content of formed free amino acid by means of thin-layer chromatography. The indicator was ninhydrin. At room temperature we did not find any trace of amino acid despite little loss in the molecular weight being detected (**36b**). At the higher temperature (**36c–e**) the conversion is between 5 and 10% regarding

Table 4 Properties of polyurethane from butyl bis(2-isocyanato-L-propanoate) (**21**) and butane-1,4-diol (BD14)

Compound	Ratio	M_n (by g.p.c.)	M_w (by g.p.c.)	T_g (°C)	Elongation at break (%)	Tensile strength (MPa)	Shore A hardness
28	**21**/BD14 = 1/1	6000	15000	53	40	32	50

In comparison: polyurethane from butyl bis(β-isocyanato propanoate): m.p. 135°C
polyurethane from MDI: m.p. 185°C

Table 5 Mechanical properties of cross-linked polyurethanes based on butyl bis(α-isocyanato-L-propanoate)

Compound	Ratio	T_g (°C)	Elongation at break (%)	Tensile strength (MPa)	Shore A hardness
33	PTMEG/BuIP/Glyc = 1/4/3	36	150	37	28
34	BuIP/Glyc = 1/1	45	80	28	63
35	BuIP/L30 = 1/1	55	15	14	90

BuIP, butyl bis(α-isocyanato-L-propanoate) (**21**); PTMEG, poly(tetramethylene ether)glycol, M_n = 650; Glyc, glycerol; L30, poly(DL)-lactide-triglyceride, M_n = 1900 (**18**)

Table 6 Degradation behaviour of an oligomer from butyl bis(α-isocyanato-L-propanoate) (**21**) and butane-1,4-diol

Compound **36**	Run	Temperature (°C)	Time (h)	Storage medium	M_n	M_w	Conversion[a]
a	Initial material	25	–	–	1980	5815	0
b	1	25	3624	Relative humidity 80%	1400	4534	0
c	2	115	52	Distilled H_2O	776	1225	5
d	3	115	52	Buffer pH 7.15	664	1155	8
e	4	115	52	0.1 M NaCl	559	797	10

[a] Conversion with respect to free amino acid

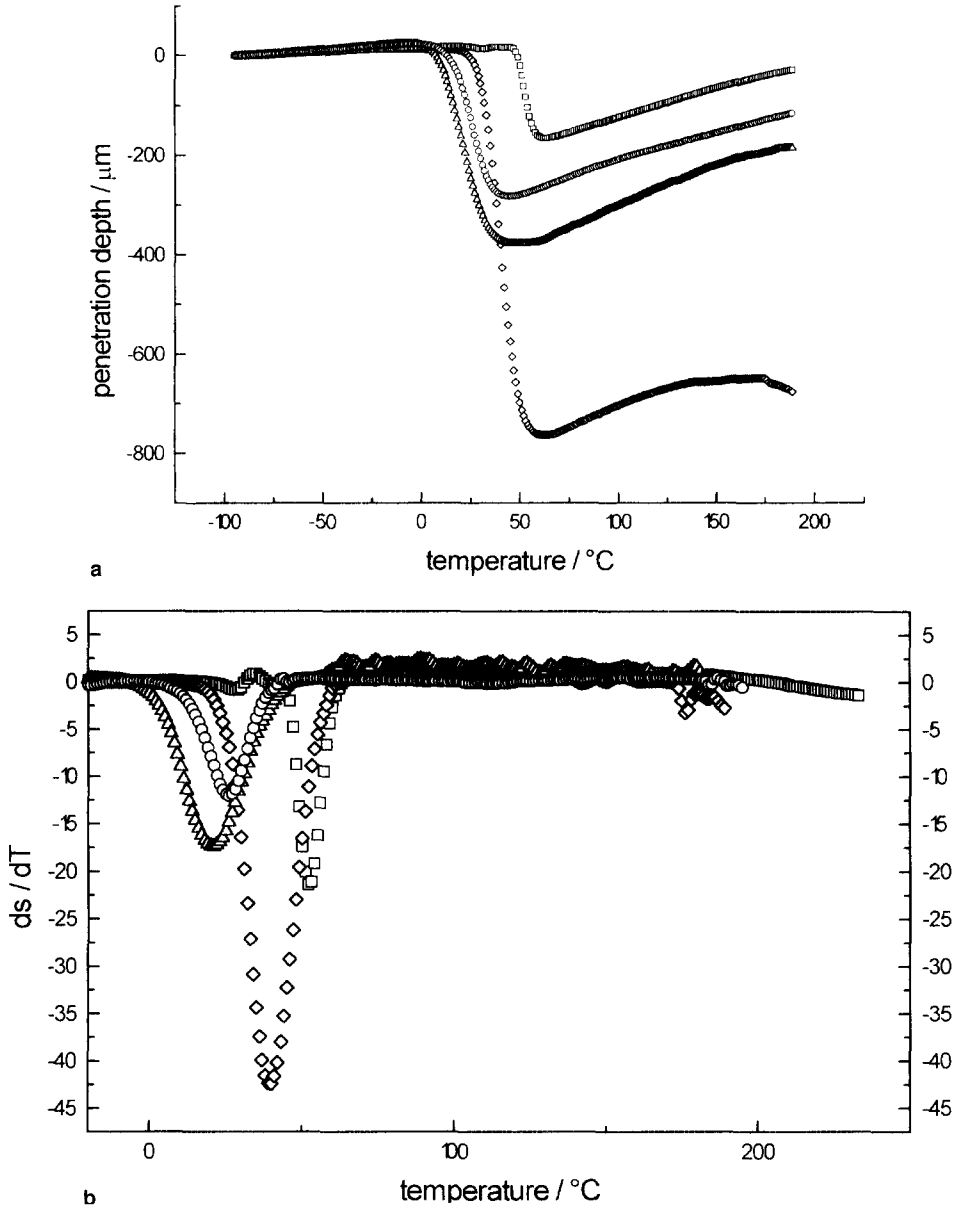


Figure 6 (a) Thermomechanical plots of model polyurethanes based on α-amino acids. (b) Corresponding differentiated thermomechanical plots. □, Butyl-1,4-bis-(L-isocyanato-propanoate)/glycerol = 1/1 (**29**); ◇, propyl-1,2-bis-(DL-isocyanato-propionate)/PTMEG 650/glycerol = 4/1/3 (**30**); △, butyl-1,4-bis-(L-isocyanato-propionate)/PTMG 650/glycerol = 3/1/2 (**31**); ○, propyl-1,3-bis-(DL-isocyanato-propionate)/PTMEG 650/glycerol = 4/1/3 (**32**)

free amino acid. The highest degradation proceeds in saline solution. Overall, the hydrolytic degradation seems to take a relatively long time.

CONCLUSIONS

Poly(isocyanato esters) can be obtained in high purity and good yield from mono-α-amino acids and common polyols. The new products react without catalysts by the conventional polyaddition procedure to form polyurethanes. By reaction with trifunctional hydroxyl compounds, tough elastic materials are produced that are hydrolytically degradable.

Mono-α-amino acids can thus be usefully applied to the preparation of degradable polyurethanes via their isocyanato ester derivatives. Important sources for fully biodegradable and resorbable materials may be compounds of glycerol, castor oil, glycine and alanine as well as low molecular weight hydroxyl-terminated oligolactides.

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