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Selective Reduction of Carbonyl Compounds with Diisopinocampheylhaloboranes

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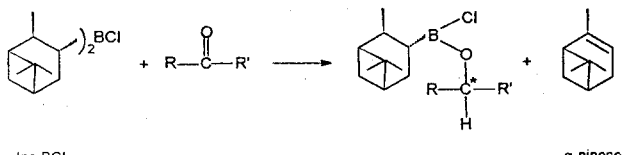
Reaction of carbonyl compounds with diisopinocampheylhaloboranes (Ipc_2BX, X=Cl, Br, I) was investigated in detail in order to establish their usefulness as selective reducing agents. The reagents reduced aldehydes and ketones to the corresponding alcohols. The reactivities are in the order of $Ipc_2BCl \gg Ipc_2BBr > Ipc_2BI$. The reagents also reduced α,β-unsaturated aldehydes and ketones to the corresponding allylic alcohols without any detectable 1,4-reduction. Especially, the chloro derivative nicely achieved the selective reduction of aldehyde or ketone groups in the presence of many other functional groups. The most remarkable result of this investigation is that aldehydes and ketones can be selectively reduced in the presence of acid chlorides.

Introduction

Chiral diisopinocampheylchloroborane (Ipc_2BCl) has proven to be extremely efficient for the asymmetric reduction of a wide variety of ketones to obtain chiral alcohols in high enantioselectivities.[1~5] The mechanism of the reduction is explained *via* a cyclic boatlike transition state.[3] The formation of an intermediate alkoxyborane is accompanied by the liberation of α-pinene[3] (Eq. 1). This fascinating reagent attracted



Ipc_2BCl α-pinene

us to investigate its general reducing characteristics in greater detail. Subsequently, we found that the reagent readily reduces α,β-unsaturated aldehydes and ketones to the corresponding allylic alcohols, and permits the selective reduction of aldehyde and ketone groups in the presence of many other functional groups.

Midland and co-workers reported that *B*-alkyl-9-borabicyclo[3.3.1]nonanes (*B*-R-9-BBN) are effective for the reduction of aldehydes, but not for ketones under mild conditions.[6,7] These results indicate that the reduction power of dialkylchloroborane is stronger than that of trialkylborane, particularly in the reduction of carbonyl compounds. The halogen attached to the boron atom seems to exert an additional influence in reduction power.

Accordingly, we decided to extend our investigation to other derivatives, Ipc_2BBr and Ipc_2BI. We prepared a series of diisopinocampheylhaloboranes (Ipc_2BX, X=Cl, Br, I), examined their reactivity toward general organic functional groups, and finally investigated their selectivity in the reduction of carbonyl compounds, in the hope of better understanding the nature of reagents and exploring their role in organic synthesis.

A portion of our results has appeared in the form of preliminary communications.[8,9] We now described in full the results of our study on the reduction characteristics of diisopinocampheylhaloborane.

Results and Discussion

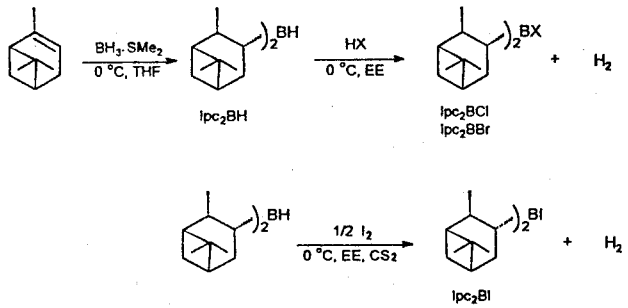
Ipc_2BCl and Ipc_2BBr were prepared from α-pinene by hydroboration followed by treatment with dry hydrogen chloride (HCl) or hydrogen bromide (HBr) in diethyl ether (EE)

Table 1. Reduction of Aldehydes and Ketones with Diisopinocampheylhaloborane (Ipc_2BX) in Pentane at 0 °C[a]

Compound	Time, h	Yield, %[b]		
		Ipc_2BCl	Ipc_2BBr	Ipc_2BI
Butanal	1	100	45	30
	24	–	80	60
Hexanal	3	100	10	6
Benzaldehyde	1	100	20	15
	3[c]	100	–	–
Cyclohexanone	3	100	–	–
	24	–	70	50
2-Methylcyclohexanone	3[d]	100	–	–
	24[d]	–	86	55
2-Heptanone	6	97	–	–
	12	100	–	–
	24	–	60	40
Norcamphor	24[d]	100	90	60
2-Hexenal	1	95	–	–
	3	100	–	–
	6[d]	–	55	30, 80[e]
3-Penten-2-one	1	60	30[d]	–
	6	90	60[d]	30[d,e]
	24	100	70[d]	55[d,e]
2-Cyclohexenone	1	95	10, 40[d]	–
	3	100	15, 50[d]	–
	6	–	15, 70[d]	40[d,e]

[a]Ten % excess reagent was utilized except where otherwise indicated. [b]GC yields with suitable interal standards. [c]At −30 °C. [d]Two equivalents of reagent utilized. [e]At 25 °C.

(Eq. 2). Removal of EE followed by addition of pentane provided a solution of Ipc_2BCl or Ipc_2BBr in pentane.[1~5] Ipc_2BI was made by reaction of Ipc_2BH (suspended in EE) with I_2 (dissolved in CS_2) (Eq. 3).

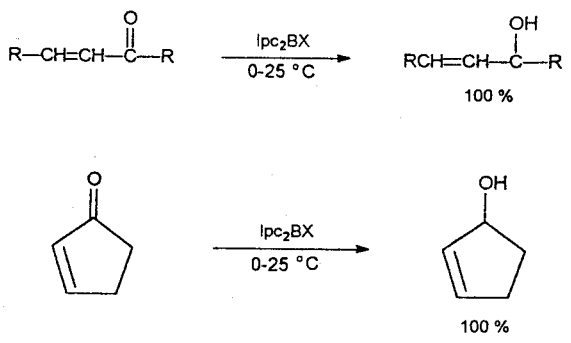


Reactivities toward Aldehydes and Ketones. The reactivities of Ipc_2BX toward some representative aldehydes and ketones were examined and the results are summarized in Table 1. In general, the reactivities are in the order of $Ipc_2BCl \gg Ipc_2BBr > Ipc_2BI$. Ipc_2BCl readily reduced a wide variety of aldehydes and ketones to the corresponding alcohols at 0 °C. However, the bromo and iodo derivatives showed much weaker reactivities, requiring an elevated reaction temperature to 25 °C or an excess reagent. The reactivity difference may be attributed to the steric and electronic effects of the halogen substituent. The striking feature of the reagents observed from the results is their rate differences toward various carbonyl compounds and their ability to reduce α,β-unsaturated aldehydes and ketones to allylic alcohols. This interesting characteristics led us to investigate their chemoselectivities in the reduction of aldehydes and ketones in detail.

Chemoselectivities in the Reduction of α,β-Unsaturated Aldehydes and Ketones. Selective 1,2-reduction of α,β-unsaturated aldehydes and ketones with metal hydride reducing agents is often difficult to achieve in organic synthesis due to competing 1,2- *vs.* 1,4- attack by hydride.[10] Among the various reducing systems which have been devised for such purpose, diisobutylaluminum hydride (DIBAH),[11] lithium aluminum hydride (LAH),[12] 9-borabicyclo[3.3.1]nonane (9-BBN),[13] lithium *n*-butylborohydride,[14] and sodium borohydride in aqueous methanol containing rare earth chlorides[15] are generally the most efficient and convenient.[16] However, these can by no means be adapted as a very general procedure.[13,15,17,18] Accordingly, it appeared desirable to examine the chemoselectivities of Ipc_2BX in the reduction of α,β-unsaturated aldehydes and ketones.

The reductions were carried out by the addition of a solution of Ipc_2BX in pentane[1~5] (generally, 10% excess of Ipc_2BCl and 2 equivalents of Ipc_2BBr or Ipc_2BI) to the carbonyl compound in pentane at 0 °C or 25 °C. The results are summarized in Table 2.

Reduction of simple conjugated aldehydes, such as crotonaldehyde, 2-hexenal and cinnamaldehyde, afforded exclusively the corresponding allylic alcohols, resulting only from 1,2-reduction. Use only a 10% excess of Ipc_2BCl at 0 °C is necessary for the complete reduction. However, the reduction with Ipc_2BBr and Ipc_2BI required a large excess of reagent (2 equivalents) and an extended reaction time or an elevated reaction temperature (25 °C). The excess reagent and elevated reaction temperature did not affect the selectivity. α,β-Unsaturated and ketones, such as 3-penten-2-one, benzalacetone and chalcone, were also selectively converted into the corresponding allylic alcohols at 0 °C or 25 °C. 2-Cyclohexenone was converted to 2-cyclohexenol in a quantitative yield. Even 2-cyclopentenone, known for its susceptibility to undergo conjugate reduction, was cleanly converted to the desired 2-cyclopentenol in a quantitative yield. Similarly, isophorone was readily reduced to 3,3,5-trimethyl-2-cyclohexen-1-ol.



Results summarized in Table 2 clearly reveal that the reagents are ideal for the selective reduction of α,β-unsaturated aldehydes and ketones to the corresponding allylic alcohols. The selectivity reaches 100%.

Table 2. Reduction of α,β-Unsaturated Aldehydes and Ketones with Ipc_2BX in Pentane[a]

Compound	Reagent	Temp, ℃	Time, h	Product ratio,[b] 1,2 : 1,4	Yield, %[b]
Crotonaldehyde[c]	Ipc_2BCl	0	3	100 : 0	>99.9(72)
	Ipc_2BBr[e]	0	48	100 : 0	95
	Ipc_2BI	25	24	100 : 0	98
2-Hexenal[c]	Ipc_2BCl	0	3	100 : 0	>99.9
	Ipc_2BBr	0	48	100 : 0	90
	Ipc_2BI	25	48	100 : 0	95
Cinnamaldehyde[c]	Ipc_2BCl	0	12	100 : 0	>99.9(69)
		0[f]	6	100 : 0	100
	Ipc_2BBr	0	48	100 : 0	95
	Ipc_2BI	25	48	100 : 0	85
		25	144	100 : 0	100
3-Penten-2-one[d]	Ipc_2BCl	0	24	100 : 0	100
	Ipc_2BBr	0	24	100 : 0	70
	Ipc_2BI	25	24	100 : 0	55
Benzalacetone[c]	Ipc_2BCl	0	24	100 : 0	50
		25	24	100 : 0	>99.9
	Ipc_2BBr	25	48	100 : 0	95
	Ipc_2BI	25	48	100 : 0	75
Chalcone[c]	Ipc_2BCl	25	72	100 : 0	>99.9
		25[f]	24	100 : 0	100
	Ipc_2BBr	25	48	100 : 0	70
	Ipc_2BI	25	48	100 : 0	65
2-Cyclohexenone	Ipc_2BCl	0	3	100 : 0	>99.9
	Ipc_2BBr	0	48	100 : 0	100
	Ipc_2BI	25	72	100 : 0	100
2-Cyclopentenone	Ipc_2BCl	0	3	100 : 0	>99.9
	Ipc_2BBr	0	48	100 : 0	100
	Ipc_2BI	25	72	100 : 0	100
Isophorone	Ipc_2BCl	0	12	100 : 0	100
		0[f]	6	100 : 0	100
	Ipc_2BBr	0	24	100 : 0	90
		0	48	100 : 0	95
	Ipc_2BI	25	24	100 : 0	90

[a]Ratios for reagent : compound were 1.1 : 1 (for Ipc_2BCl) and 2 : 1 (for Ipc_2BBr and Ipc_2BI), except where otherwise indicated. [b]Determined by GC using calibrated internal standard, numbers in parentheses indicate isolated yields. [c]A *trans* isomer. [d]A mixture of 69 % 3-penten-2-one and 31 % mesityl oxide; the same ratio of 3-penten-2-ol and 4-methyl-3-penten-2-ol was obtained. [e]Ten % excess reagent was utilized. [f]Two equivalents of reagent were used.

Chemoselectivities in the Competitive Reduction between Carbonyl Compounds. Chemoselective reduction of one carbonyl group in the presence of other such groups affords an important methodology in organic synthesis. In recent years, various reagents have been developed for such selective reductions.[20] These reagents are mostly capable of reducing aldehydes in the presence of ketones, and only a few reagents have been reported for the selective reduction between structurally different ketones.[21] Moreover, no report has appeared for the selective reduction of carbonyl compounds in the presence of acid chlorides.

As shown in Table 3, the remarkable feature of Ipc_2BCl is its ability to selectively reduce aldehydes in the presence of ketones. Thus aldehydes are reduced almost completely in one hour at 0 ℃, whereas, under similar experimental conditions, ketones require a much longer reaction time. This rate difference between aldehyde and ketone led us to further examine the chemoselectivity of Ipc_2BCl. The chemoselectivity of Ipc_2BCl was studied by competitively reducing the equimolar mixture of two carbonyl compounds with one equivalent of Ipc_2BCl. And, it was tested for three representative aldehyde-aldehyde pairs (entries 1-3), five aldehyde-ketone pairs (entries 4-8), six ketone-ketone pairs (entries 9-14), and six aldehyde or ketone-other reducible compound pairs (entries 15-20). The results are summarized in Table 3.

As listed in Table 3, Ipc_2BCl exhibits a relatively low chemoselectivity between aldehydes. However, the reagent achieves a selective reduction of aldehydes in the presence of ketones. Thus, both aliphatic and aromatic aldehydes can

Table 3. Competitive Reduction of Aldehydes and Ketones with Ipc_2BCl in Pentane[a]

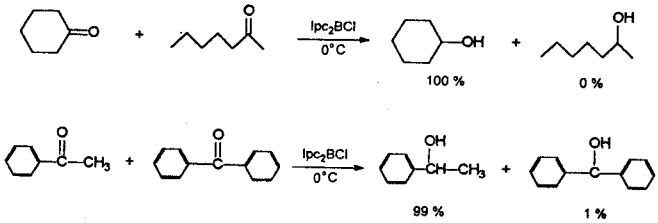
Entry	Starting Mixture	Temp, ℃	Time, h	Ratio of redn products[b]
1	Benzaldehyde/Hexanal	0	1	60 : 40
		−30	3	80 : 20
2	Benzaldehyde/*p*-Anisaldehyde	0	1	60 : 40
3	Hexanal/*p*-Anisaldehyde	0	1	60 : 40
4	Butanal/Cyclohexanone	0	1	99.5 : 0.5
5	Hexanal/Cyclohexanone	0	3	70 : 30
		−30	3	100 : 0
6	Hexanal/2-Heptanone	0	3	100 : 0
7	Hexanal/Acetophenone	0	3	100 : 0
8	Hexanal/Benzophenone	0	3	100 : 0
9	Cyclohexanone/Cyclopentanone	0	1	65 : 35
		−30	3	80 : 20
10	Cyclohexanone/2-Heptanone	0	3	99.5 : 0.5
11	Cyclohexanone/Acetophenone	0	3	95 : 5
		−30	12	100 : 0
12	2-Heptanone/Acetophenone	0	6	50 : 50
13	2-Heptanone/Benzophenone	0	3	100 : 0
14	Acetophenone/Benzophenone	0	3	99 : 1
15	Butanal/Hexanoyl chloride	0	1	99.9 : 0.1
16	Hexanal/Hexanoyl chloride	0	3	99.9 : 0.1
17	2-Heptanone/Hexanoyl chloride	0	6	99.9 : 0.1
18	2-Heptanone/Benzoyl chloride	0	6	100 : 0
19	2-Heptanone/Hexanenitrile	0	6	99.9 : 0.1
20	2-Heptanone/Ethyl hexanoate	0	6	100 : 0

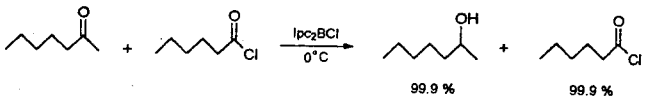
[a]Reaction mixture were *ca.* 1 M in substrats. One equivalent of reagent was utilized for the competitive reduction of equimolar mixture of two compounds. [b]Normalized ratio determined by GC with appropriate internal standard; the total yields of product alcohols were ≥99.5 %.

be selectively reduced in the presence of quite a number of various ketones showing essentially 100% selectivity. The reagent even distinguished between an aldehyde and a more reactive ketone such as cyclohexanone. The selectivity between ketones is also remarkable. Cyclohexanone was reduced selectively in the presence of 2-heptanone or acetophenone, and acetophenone was reduced much more readily than benzophenone showing a 99 : 1 selectivity.

Furthermore, the reagents are extremely mild. Even acid chloride, the most susceptible functional group, is compatible.[19] This represents major advantage of Ipc_2BX over the more conventional reagents for the reduction of enals and enones to allylic alcohols. Especially, the chloro derivative Ipc_2BCl appears to be a reagent of choice: the compatibility with a wide variety of normally reducible functional groups, mild reaction conditions and essentially quantitative yield of reduced product in a relatively short period of reaction, coupled with the absence of side products recommend this reagent for such purpose.

The most challenging part of this experiment is the competitive reaction between a ketone and acid chloride, the most reactive functional group in organic compound. Aldehydes and ketones can be selectively reduced in the presence of acid chlorides. Also, other functional groups, such as nitrile and ester, are not affected by Ipc_2BCl under these reaction conditions. Consequently, the reagent permits the selective reduction of aldehyde or ketone groups in the presence of many other functional groups.





Conclusion

The utility of diisopinocampheylhaloboranes (Ipc_2BCl; X = Cl, Br, I) as chemoselective reducing agents for aldehydes and ketones has been demonstrated in this study. Especially, the chloro derivative shows an essentially 100% chemoselectivity in the reduction of α,β-unsaturated carbonyl compounds to allylic alcohols and in the competitive reduction between carbonyl compounds. The reagent is exceptionally mild and the reaction proceeds smoothly at 0° or 25 ℃ in pentane. In addition to its previously known high enantioselectivity in the reduction of prochiral ketones,[1~5] these new chemoselectivities of the reagent should find wide application in organic synthesis.

Experimental Section

All glassware used in this study was predried at 140 ℃ for several hours, assembled hot, and cooled under a stream of dry nitrogen prior to use. All reactions and manipulations of air- and moisture- sensitive materials were carried out using standard techniques for handling air-sensitive material.[22] All chemicals were commercial products of the highest purity which were further purified by standard methods before use. Pentane was bubbled with dry nitrogen, dried with molecular sieve (4 Å) and distilled. Borane-methyl sulfide (BMS) and α-pinene were purchased from Aldrich Chemical Co. GC analyses were performed on a Hewlett-Packard 5790 A FID chromatograph equipped with a Hewlett-Packard 3390 A integrator/plotter, using a 12 ft.×0.125 in. column of 10% Carbowax 20 M on 100-120 mesh Supelcoport or a 10% Carbowax 20 M capillary column (25 m). ^{11}B NMR spectra were recorded on a Bruker AMX-300 spectrometer and ^1H NMR spectra were recorded on a Varian EM-360A instrument. The chemical shifts are with reference to $BF_3 \cdot OEt_2$ and tetramethylsilane, respetively.

Preparation of Diisopinocampheylhaloborane (Ipc_2BX)

(a) Diisopinocamphenylchloroborane (Ipc_2BCl). To Ipc_2BH (100 mmol), prepared from (+)-α-pinene (210 mmol) and BMS (100 mmol) in THF (96 mL) at 0 ℃ for 6 h,[23] suspended in EE (50 mL) at −78 ℃ in a 250-mL round-bottom flask containing a magnetic stirring bar and fitted with a septum-capped sidearm and a connecting tube, was added dry HCl[24] (40.0 mL of 2.50 M solution in EE). The mixture was stirred for 15 min at −78 ℃, warmed to 0 ℃ and stirred at that temperature until all of the solid dissolved and gas evolution ceased (2 h). The EE was pumped off and 50 mL of pentane was added. The ^{11}B NMR spectrum showed a singlet at δ 75 ppm.

(b) Diisopinocampheylbromoborane (Ipc_2BBr). HBr in EE was prepared from hydrobromic acid and phosphorus in ethyl acetate using an automatic gasimeter. The solution was standardized using standard NaOH. To Ipc_2BH (10 mmol) suspended in EE (96 mL) at 0 ℃ was added 44.45 mL of 2.25 M HBr[24] in EE and the mixture was stirred till all of the solid dissolved and gas evolution ceased (3 h). The EE was pumped off and 50 mL of pentane was placed. The ^{11}B NMR spectrum showed a singlet at δ 78.

(c) Diisopinocampheyliodoborane (Ipc_2BI). Into a 250-mL flask containing a freshly-prepared solid of Ipc_2BH (50 mmol) was added 50 mL of EE and the flask was immersed into an ice-water bath. To the slurry suspended in EE was added dropwise a 1 M solution of I_2 (25 mL, 25 mmol) in CS_2 and the mixture was stirred at that temperature until all of the solid dissolved and gas evolution completed (2 h). All the solvents were pumped off and 30 mL of pentane was added. The ^{11}B NMR spectrum showed a singlet at δ 85.

General Reduction Procedure

The following procedure was used to examine the rate of reduction of carbonyl compounds with Ipc_2BX. In an oven-dried, 10-mL, round-bottom flask equipped with a septum-capped sidearm and a magnetic stirring bar was placed 10% excess of Ipc_2BX in pentane (5.5 mmol) and a suitable internal standard. The flask was maintained at 0 ℃ by an ice-water bath. To this was added 5 mmol of a carbonyl compound tested and the mixture was stirred. At the appropriate time intervals, an aliquot was withdrawn and quenched with aqueous NaOH. The organoborane was oxidized by addition of 30% H_2O_2. The aqueous layer was saturated with K_2CO_3, and the organic layer was separated and dried with anhydrous $MgSO_4$. The organic layer was subjected to GC analysis and the rate of reduction was estimated.

Reduction of α,β-Unsaturated Carbonyl Compounds to Allylic Alcohols

The following procedure for the reduction of crotonaldehyde with Ipc_2BCl is representative. An oven-dried, 25-mL flask equipped with a sidearm fitted with a rubber stopple, a magnetic stirring bar, and a reflux condenser connected to a mercury bubbler was cooled down to room temperature under nitrogen. Pentane (1 mL) was injected into the flask followed by 0.42 mL (5 mmol) of crotonaldehyde (freshly distilled) and 0.60 mL (2.5 mmol) of *n*-tridecane. The reaction flask was cooled to 0 ℃ (ice-water bath) and 2.8 mL (5.6 mmol) of a 2 M Ipc_2BCl solution in pentane was added. The mixture was stirred for 3 h at 0 ℃. The reaction mixture was then hydrolyzed and oxidized (NaOH-H_2O_2, 25 ℃, 2 h). The aqueous layer was saturated with K_2CO_3 and the dry pentane layer was subjected to GC analysis, indicating the presence of crotyl alcohol as a sole product in >99.9% yield.

In a larger scale of reaction, crotonaldehyde (2.80 g, 40 mmol) was reduced with Ipc_2BCl (44 mmol) in pentane at 0 ℃. When the reaction was complete (3 h), acetaldehyde (2.8 mL, 49.5 mmol) was added dropwise. The mixture was then warmed to room temperature and stirred for 3 h. Sodium hydroxide (6 N, 40 mL) was added to the mixture and the organics were extracted with diethyl ether. The combined extracts were washed with brine, dried over $MgSO_4$, and distilled to separate crotyl alcohol (2.60 g, 72%) and α-pinene (10.4 g, 90%).

Competitive Reduction

The following competitive reduction between cyclohexanone and acetophenone is representative. In a 50-mL, round-bottom flask was placed 5.0 mmol each of cyclohexanone and acetophenone solution (2 M) in pentane, followed by 0.60 mL of *n*-tridecane. The flask was kept at −30 ℃ with the aid of a cooling bath. To this flask was added 2.5 mL of a 2.0 M solution of Ipc_2BCl in pentane (5.0 mmol) with vigorous stirring. The reaction mixture was stirred at −30 ℃ for 12 h. It was then hydrolyzed with 2 mL of 2 N NaOH, and then the organoborane was oxidized with 1 mL of 30% H_2O_2 for 2 h at room temperature with stirring.[25] After oxidation, the aqueous layer was saturated with K_2CO_3 and the separated organic layer was dried with anhydrous $MgSO_4$. GC analysis of the pentane layer showed a 100% yield of cyclohexanol and a 100% yield of recovered acetophenone, indicating no presence of α-phenylethanol.

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24. Dry HCl and HBr were prepared from hydrochloric acid-sulfuric acid and hydrobromic acid-phosphorus tribromide in ethyl acetate, respectively, using a Brown apparatus.[22]
25. In the case of aldehyde-aldehyde or aldehyde-ketone pairs, a buffer solution (pH 7.0) was added before the oxidation step in order to avoid the possible oxidation of unreacted starting aldehyde.