

The Application of Ionic Liquids in Cathodic Coupling of Acetophenone

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Abstract: Problem statement: The cathodic coupling of acetophenone was carried out in aqueous solutions containing sodium sulfate and 1-Octyl-3-Methylimidazolium Chloride ([OMIM]Cl) as supporting electrolytes. [OMIM]Cl is an ionic liquid, also serving as a co-solvent to prevent the deposition of products during electrolysis. The products are extracted with ether after electrolyses. **Approach:** It is shown in this study that the recycling of the aqueous Na₂SO₄-[OMIM]Cl electrolytes is feasible. **Results:** The new electrolytic process is more energy saving and environment-friendly than conventional ones. **Conclusion:** On the other hand, the ratios of dl-to meso pinacols formed in the electrochemical reduction of acetophenone can be more than 9, higher than ever reported for any aqueous system.

Key words: Ionic liquids, cathodic coupling, acetophenone

INTRODUCTION

There has been a practical problem for most electroorganic reactions. Supporting electrolytes are necessary to pass the current through the electrolytic cell. However, the solubility of organic compounds in water is generally so low that organic solvents are preferred. Therefore, expensive quaternary ammoniums are used rather than cheap salts such as sodium sulfate, because these inorganic salts are insoluble in organic solvents. After electrolysis, the organic solvent is evaporated, the products are extracted and the quaternary ammonium is left in water phase. The conventional electrolysis process is not ideal at all when considering the following two questions:

- How to recycle of the expensive quaternary ammoniums?
- How to reduce the energy cost due to the high resistance of the cell when organic solvents are used?

Recently, there is a boom to apply ionic liquids on conventional reactions. Ionic liquids are inherently quaternary ammoniums. The role of quaternary ammoniums seems not simply to be supporting electrolyte, the function as catalyst is also possible. In addition, ionic liquids could be used as solvents to dissolve the reactants (Hapiod and Lagrost, 2008). Because of the immiscibility of ionic with most organic solvents and supercritical fluids, the products can be extracted after electrolysis, then the electrolytes containing ionic liquids can be ideally recycled for next electrolysis. This study is therefore aimed to pioneering a new way, which could be more energy-saving and environment-friendly than conventional electroorganic syntheses.

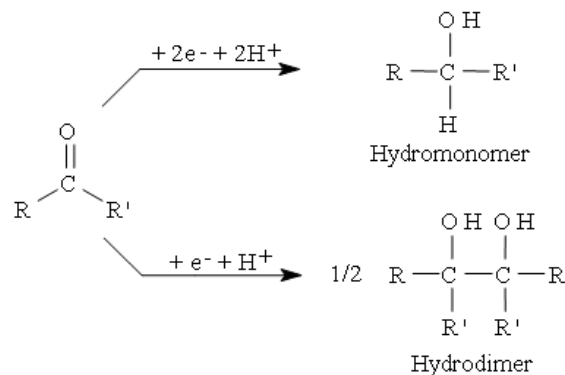


Fig. 1: The reaction scheme for the electroreduction of carbonyl compounds

Electroreduction of carbonyl compounds is a typical organic reaction using electrons as reagents. Generally, hydromonomer and hydrodimer are obtained simultaneously (Fig. 1).

There have been many studies concerning how to control the product-selectivity of hydrodimer to hydromonomer. Controlled potential electrolysis is generally effectual (Kodama *et al.*, 2001; Janssen, 1988). Alternatively, a better mass-transfer condition can favor the production of hydrodimer under galvanostatic operation (Cheng and Nonaka, 1989; 1991; Cheng *et al.*, 1991). Aqueous electrolytes without organic solvents are possible for electroreduction of acetophenone, if the substrate concentration is low enough and surfactants such as cetyltrimethylammonium bromide is used (Kodama *et al.*, 2001). If ionic liquids are used rather than the common

quaternary ammoniums, solid at room temperature, what will be different in product-selectivity? This is one of the concerns in this research.

On the other hand, the stereo-selectivity of this reaction has been so interesting and investigated extensively. It is found the dl/meso ratio of hydrodimer can vary from 0.3-19. Proton is a key factor, it is implied that aprotic environment favors the formation of dl-hydrodimer (Bewick and Brown, 1977; Bewick and Cleghorn, 1973; Smith and Utley, 1981; Stocker and Jenevein, 1968b; 1969; Maurice *et al.*, 2000). It has been shown that the stereo-selectivity can also be influenced by ionic liquids. Lagrost *et al.* have found that the electroreduction of acetophenone using an imidazolium-based ionic liquid ([BMIM][NTf₂]) resulted in a significantly lower dl/meso ratio (1.1) than those using trimethylbutylammonium and triethylbutylammonium salts did (3.3 and 3.7) (Lagrost *et al.*, 2005). It is supposed that the interaction between imidazolium cations and acetophenone radical anions leads to the formation of ion-pairs, and coupling from two ion-pairs decreases the stereo-selectivity of the reaction. Initially, this study is aimed to selectively obtain meso-hydrodimer by using imidazolium-based ionic liquids. However, unexpected results are shown in the following experiments.

MATERIALS AND METHODS

Reagents and materials: In this study, 1-Octyl-3-Methylimidazolium Chloride ([OMIM]Cl) is selected as an imidazolium-type ionic liquid. It can be prepared from inexpensive materials and in high yield (Huddleston *et al.*, 2001).

Acetophenone and 1-phenyl-1-ethanol (hydromonomer) are commercially available and were used without purification. The commercial available 2,3-diphenyl-2,3-butanediol (hydrodimer) is a mixture of dl- and meso-forms, n-hexane was used to recrystallized and separate the dl-form. The filtrate containing mainly meso-form was concentrated and transferred to an alumina column, then the meso-form was isolated by elution with benzene.

Deionized and distilled water was used for the preparation of aqueous solutions. All other reagents and solvents used are analytical grade. Electrode materials were purchased from Alfa Aesar.

Electrolysis: The electrolytic cell is a H-cell divided by an Ionic MC-3470 cationic membrane (Sybron Chemicals Inc., USA). The cell is equipped with a copper or lead cathode and a graphite anode, both cylinder and with the same exposed area of 10 cm².

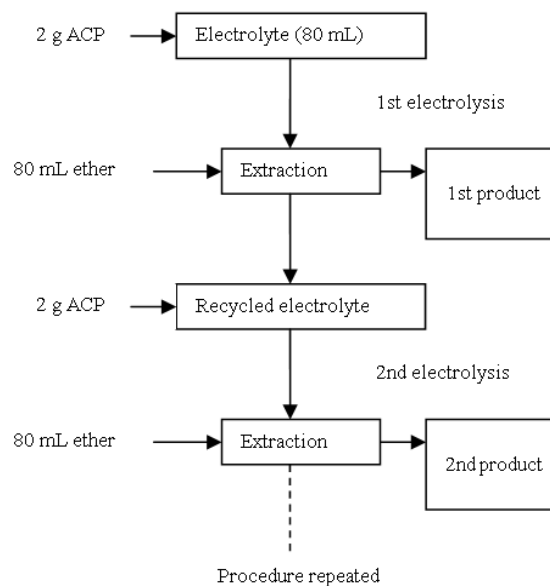


Fig. 2: Electrolyte recycling scheme

Before electrolysis, Cu cathode was polished with 0.3 μm Al₂O₃ and rinsed twice for 10 min with distilled water in an ultrasonic bath. Pre-electrolysis without carbonyl compounds was carried out for ca. 15 min in 0.5 M Na₂SO₄, unless otherwise stated. The rotation speed of the magnetic stirrer in cathodic chamber was set high enough to make emulsions in cases that immiscible co-solvents were used. The details of the electrolytic conditions are shown in Table 1 and 2.

According to the results in Table 1, the electrolytic conditions are modified for the test to recycle the electrolytes as shown in Fig. 2. The charge passed is 1.2 F for each cycle

Analysis: After electrolysis, the catholyte was repeatedly extracted with the same volume of ether for 4 times. The combined extract was washed with a saturated NaCl solution and then dried over Na₂SO₄. After filtration, ether was evaporated and the residue was dissolved in isopropanol. The products were routinely analyzed using HPLC (Cheng *et al.*, 1991; Cheng and Nonaka, 1991).

RESULTS AND DISCUSSION

Effect of co-solvents: The preliminary results are shown in Table 1. The best current efficiency for hydrodimer was 42% (Run 6) and 63% of acetophenone was converted to pinacol. The dl-form of pinacol is the major product. The yield of hydromonomer is generally no more than meso-pinacol, except in Run 4.

Table 1: Isomeric ratios and current efficiencies in cathodic coupling of Acetophenone (ACP). Here aq, EA, and IL represent 0.5 M Na₂SO₄(aq), ethyl acetate and [OMIM]Cl, respectively. The charge passed is 1.5 F, except for Run 1, in which is 2.0 F. The cathode is Cu, and the anolyte is 0.5 M Na₂SO₄

Run	Catholyte			Current density/ mAcm ⁻²	Current efficiency/%		
	aq mL ⁻¹	Co-solvent	ACP g ⁻¹		Hydrodimer	Hydromonomer	dl/meso
1	70	10 g IL	2.0	10	28	1.2	8.4
2	60	4 g IL	2.0	10	38	1.9	4.4
3	70	16 mL EtOH 2 g IL 8 mL EA	2.0	10	36	12.0	2.9
4	60	20 g IL	4.0	20	38	1.0	7.9
5	60	20 g IL	2.0	20	34	2.6	6.9
6	60	20 g IL	2.0	10	42	2.3	9.2
7	60	20 g IL	1.0	10	30	1.8	9.7

Table 2: Influence of catholyte compositions. The catholyte is prepared by adding 2.0 g of acetophenone and 20 g of [OMIM]Cl into 60 mL of aqueous solution of salts in 0.5 M. Current density is 10 mA cm⁻², and the charge passed is 1.5 F. 0.5 M of the corresponding inorganic salt is used as anolyte

Run	Cathode	Salt*	Current efficiency/%		
			Hydrodime	Hydromonomer	dl/meso
8	Cu	Al ₂ SO ₄	5.2	4.0	1.6
9	Pb	Al ₂ SO ₄	37.0	21.0	1.8
10	Cu	Na ₃ PO ₄	43.0	4.8	7.7
11	Pb	Na ₃ PO ₄	67.0	15.0	7.7
12	Cu	Na ₃ Cit	49.0	7.7	8.1
13	Pb	Na ₃ Cit	45.0	15.0	8.1
14	Pb	MgSO ₄	~0.0	5.2	-

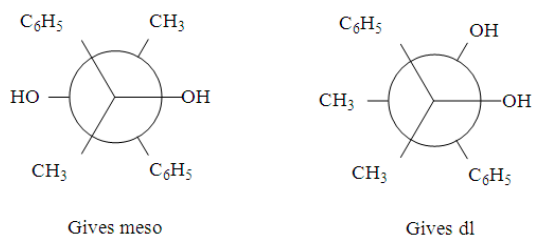


Fig. 3: The staggered conformation of 2,3-diphenyl-2,3-butanediol. In meso form, bond moments exactly cancel each other out, leading to be nonpolar

The high ratios of dl-to meso-pinacol are extraordinary, because the reactions are processed in aqueous solutions. The reported dl/meso ratio seems not to exceed 4 for any protic environment, although more than 10 values are not rare for aprotic systems (Bewick and Brown, 1977; Bewick and Cleghorn, 1973; Smith and Utley, 1981).

There were solid precipitates during electrolysis in Runs 1 and 2. These are not regarded as good electrolytic conditions. To avoid product precipitates, it is common to use more co-solvents such as ethanol or methanol. In more cases, aprotic solvents such as acetonitrile or DMF are favored. As a co-solvent, [OMIM]Cl is better than ethanol, the voltage of the

electrolytic cell is lower, and the products are more soluble in the aqueous mixture. If the organic solvent is not miscible with aqueous solution, the system will be an emulsion (Run 3). Emulsion electrolysis has its advantages, however, it is more complicated to control, because cathodic coupling possibly occurs in both aqueous and organic phases. It is evident that co-solvents other than [OMIM]Cl result in lower dl/meso ratios.

Water has a very high dielectric constant. By mixing [OMIM]Cl with aqueous Na₂SO₄, most electrolytes in the present research are considered to be much more polar than those protic environments in references.

meso-Pinacol is nonpolar when it rotates to the staggered conformation, but dl-pinacol can not be (Fig. 3). Therefore, it is considered that more polar environment favors the production of dl-pinacol. The preference for the dl isomers has been generally attributed to inter-radical hydrogen bonding during dimerization (Stocker and Jenevein, 1968a; Pulisi *et al.*, 1969). In this work, a new point of view is presented. The polarity of electrolytic environment is considered another important factor in controlling the stereo-selectivity.

In Run 2, Ethanol (EtOH) was used as a co-solvent in addition to [OMIM]Cl, The existence of EtOH decreases the polarity of electrolytic environment and

results in the lower ratios of dl/meso. The role of [OMIM]Cl in Run 3 is more complicated because of an emulsion system. The meso-hydrodimer is considered to form mainly in the much less polar environment of organic phase.

Effect of inorganic salts and electrode materials:

Not only aqueous sodium sulfate solution is miscible with [OMIM]Cl, other salts could be also used (Table 2). The existence of ions with greater charge was expected to make the solution more polar, however, further promotion of dl/meso ratio did not succeed. It is well known that dl/meso ratio in acidic media is much less than that in neutral or basic media and the aqueous solution of aluminum sulfate is acidic. The results of Runs 8 and 9 imply that proton is more important than polar environment in controlling the stereo-selectivity. In addition, the electroreduction of acetophenone is almost suppressed by magnesium ions, as shown by very low current efficiency (Run 14). In this reaction, the cations could have many roles and further investigation is necessary to clarify the complexities.

From the viewpoint of energy cost, lead is better than copper as cathode material because of its higher hydrogen overvoltage and therefore higher current efficiency. However, relatively more hydromonomer forms on lead in basic media (Runs10-13).

Recycling test: The catholyte was reused for 4 times. The results of recycling test are shown in Fig. 4. Current efficiency of hydrodimer increases from 45% in 1st cycle to 56% in 2nd cycle, while current efficiency of hydromonomer decreases from 19% in 1st cycle to 4.6% in 2nd cycle. On the other hand, dl/meso ratio increases from 7.9-8.9.

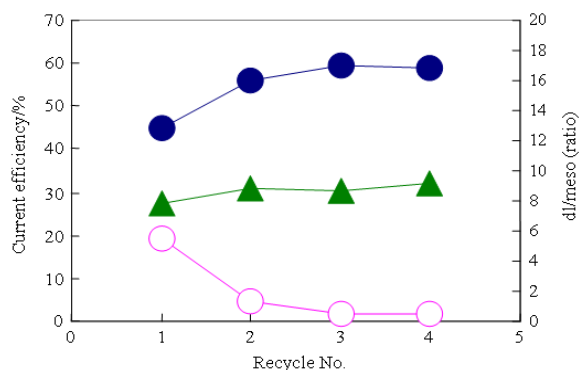


Fig. 4: Results in four recycles: Current efficiency for hydrodimer (●), current efficiency for hydromonomer (○) and dl/meso ratio (▲)

After 2nd cycle, significant changes are not observed. This is consistent with the change of pH. The catholyte was initially neutral in 1st cycle. However, the consumption of proton during electrolysis was faster than the proton transfer from anolyte chamber through cation exchange membrane, therefore, the catholyte became more basic. After 2nd cycle, reproducibility was observed, it is because pH has approached a steady value.

CONCLUSION

Since the concentration of acetophenone could be rather high in the aqueous Na_2SO_4 -[OMIM]Cl electrolytes, hydrodimer would be expected to be the major product under galvanostatic operation (Cheng and Nonaka, 1989; 1991; Cheng *et al.*, 1991) and the cell voltage could be much less than those using organic solvents as co-solvents. After extraction, the electrolyte could be recycled. Although many factors are not exactly controlled in the present study, reproducibility of this example implies that the recycling of the aqueous Na_2SO_4 -[OMIM]Cl electrolytes is feasible.

Proton should be the major factor in controlling the stereo-selectivity of hydrodimers. However, the polarity of electrolytes seems potential to enhance the formation of dl-pinacol. The high polar electrolyte has been prepared by mixing ionic liquids with aqueous electrolytes. It is courageous that high dl/meso ratios could be therefore achieved even in aqueous solutions. Further investigations are now directed to improve the stereo-selectivity for dl-hydrodimer.

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REFERENCES

- Bewick, A. and D.J. Brown, 1977. Effects of ion-pairing and adsorption of the stereochemistry of the cathodic pinacolisation of acetophenone. *J. Chem. Soc., Perkin Trans.*, 2: 99-102.
- Bewick, A. and H.P. Cleghorn, 1973. Stereochemical factors in the cathodic pinacolisation of acetophenone at a mercury pool. *J. Chem. Soc., Perkin Trans.*, 2: 1410-1413.
- Cheng, P.C. and T. Nonaka, 1989. Product-selectivity control in electroorganic reactions by mass-transfer rate. *J. Elect. Chem.*, 269: 223-230.

- Cheng, P.C. and T. Nonaka, 1991. Mass transfer and product-selectivity in electroreduction of p-Methylbenzaldehyde. *Bull. Chem. Soc. Jap.*, 64: 3500-3502.
- Cheng, P.C., T. Nonaka and T.C. Chou, 1991. Prediction of product-selectivity in an electroorganic process by mathematical modeling of reaction mechanism. A rotating cylinder electrode system. *Bull. Chem. Soc. Jap.*, 64: 1911-1915.
- Hapiot, P. and C. Lagrost, 2008. Electrochemical reactivity in room-temperature ionic liquids. *Chem. Rev.*, 108: 2238-2264.
- Huddleston, J.G., A.E. Visser, W.M. Reichert, H.D. Willauer and G.A. Broker *et al.*, 2001. Characterization and comparison of hydrophilic and hydrophobic room temperature ionic liquids incorporating the imidazolium cation. *Green Chem.*, 3: 156-164.
- Janssen, L.J.J., 1988. Cathodic Macroelectrolysis of Acetophenone: A careful analysis of product distribution. *Electrochim. Acta*, 33: 897-903.
- Kodama, Y., M. Imoto, N. Ohta, A. Kitani and S. Ito, 2001. Selective reduction of acetophenone to 1-phenylethanol in aqueous media. *J. Elect. Chem.*, 507: 103-109.
- Lagrost, C., P. Hapiot and M. Vaultier, 2005. The influence of room-temperature ionic liquids on the stereoselectivity and kinetics of the electrochemical pinacol coupling of acetophenone. *Green Chem.*, 7: 468-474.
- Maurice, C., B. Schöllhorn, I. Canet, G. Mousset and C. Mousty *et al.*, 2000. Electrochemical reduction in an aprotic medium of new functionalized amphiphilic molecules derived from sugars: Stereoselective pinacolization and an example of a glycoside carbon-oxygen bond cleavage. *Eur. J. Org. Chem.*, 813-821.
- Smith, C.Z. and J.H.P. Utley, 1981. Modification of pathways for cathodic reduction via complexation with β -cyclodextrin. *J. Chem. Soc., Chem. Commun.*, 492-494.
- Stocker, J.H. and R.M. Jenevein, 1968a. Quantitative studies in stereochemistry C. Electrochemistry, I. The ratio of diastereomeric pinacols formed in the electrolytic bimolecular reduction of acetophenone-7- C^{14} . *J. Org. Chem.*, 33: 294-297.
- Stocker, J.H. and R.M. Jenevein, 1968b. Quantitative studies in stereochemistry, electrochemistry, II. The ratio of diastereomeric glycols formed in the electrolytic bimolecular reduction of benzaldehyde and propiophenone. *J. Org. Chem.*, 33: 2145-2146.
- Stocker, J.H. and R.M. Jenevein, 1969. Quantitative studies in stereochemistry, photochemistry, VII. Electrochemistry, IV. The photochemical and electrochemical bimolecular reduction of aldehydes and unsymmetrical ketones; a common stereochemistry. *J. Org. Chem.*, 34: 2810-2813.
- Pulisi, V.J., G.L. Clapper and D.H. Evans, 1969. Stereochemistry of the electrolytic reductive coupling of benzaldehyde. *Anal. Chem.*, 41: 279-282.