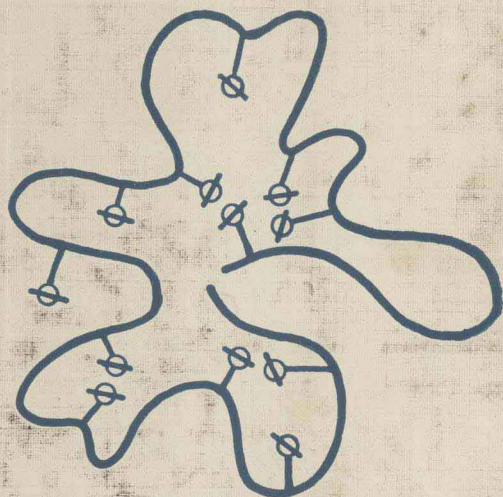


Water-Soluble Polymers

Synthesis, Solution Properties,
and Applications



EDITED BY

Shalaby W. Shalaby,
Charles L. McCormick
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Water-Soluble Polymers

Synthesis, Solution Properties, and Applications

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Foreword

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Preface

THE CONTENTS OF THIS BOOK are based primarily on the proceedings of a symposium on water-soluble polymers held during the ACS National Meeting in Miami in September 1989. This was organized as a response to a highly noted interest in this class of polymers for their distinct relevance to theoretical and applied research in biotechnology, controlled delivery of active agents, and protection of the environment. To meet the call for a comprehensive coverage of this area in one volume, authoritative investigators other than those who participated in the symposium were invited to contribute to this publication.

Contents of the volume are organized to provide the readers with fundamental information on the organic and physical chemistry of synthetic and natural polymers, as well as recent developments in polymer synthesis and modification (the first three sections). New and non-traditional applications of water-soluble polymers — particularly in the health care industry — are dealt with in the fourth section. In concert with the growing emphasis on interdisciplinary research, the editors elected to conclude the book with a brief, highly focused section on advances in less conventional systems. These pertain to topics which bridge high technology research areas in chemistry and biology, medicine, and engineering.

It is hoped that the readers of this volume will find it not only a valuable source of information, but also an inspiring lead to recognize and pursue exciting new areas of research.

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April 1991

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POLYMERS AND INTERMEDIATES

Chapter 1

Structural Design of Water-Soluble Copolymers

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Macromolecules exhibiting solubility in aqueous solutions represent a diverse class of polymers ranging from biopolymers that direct life processes to synthetic systems with enormous commercial utility. In this chapter discussion will be directed toward fundamental concepts of structural arrangement, functionality, synthesis, and solution behavior. Subsequent chapters will detail advanced synthetic methods, polymerization kinetics, solution behavior including that of polyelectrolytes, polyampholytes, and polysoaps, and a number of selected technological applications.

Solution properties and ultimate performance of water-soluble polymers are determined by specific structural characteristics of the solvated macromolecular backbone. Primary structure depends upon the nature of the repeating units (bond lengths and valence bond angles) as well as composition, location, and frequency. Macromolecules may be linear or branched with repeating units arranged in random, alternating, block, or graft fashion (Figure 1).

Secondary structure in water-soluble polymers is related to configuration, conformation, and intramolecular effects such as hydrogen bonding and ionic interactions. Tertiary structure is defined by intermolecular interactions while quaternary structure is governed by multiple-chain complexation.

The key to water solubility lies in positioning sufficient numbers of hydrophilic functional groups along the backbone or side chains. Figure 2 lists some of the major substituents that possess sufficient polarity, charge, or hydrogen bonding capability for hydration. Some biopolymers and synthetic co- and terpolymers are not totally water-soluble, but instead exist in microheterogeneous states in aqueous media. Reversible associations may be controlled to yield technologically important responses.

Synthetic Methods

Water-soluble copolymers are prepared by step-growth or chain-growth polymerization of appropriate monomers or by post-reaction procedures. Distribution of the units along the backbone or on the side chain may be accomplished in a number of ways. In nearly all procedures, proper sequencing

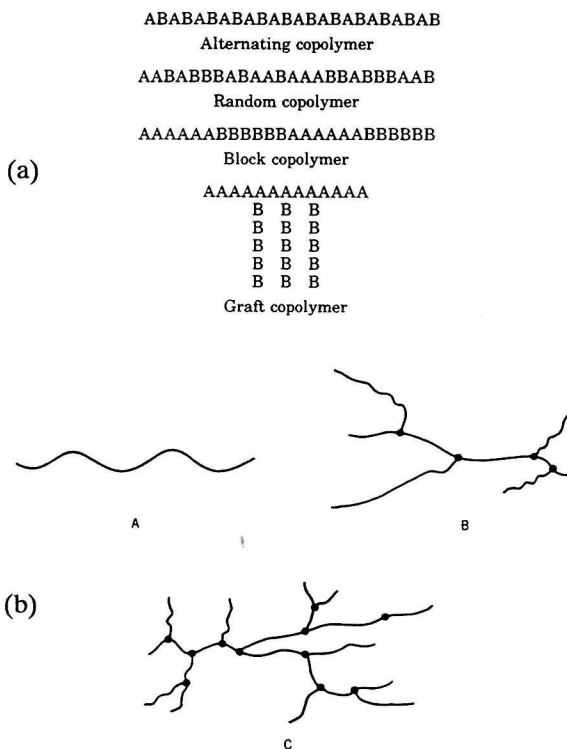


Figure 1. (a) Monomer distributions; (b) segmental disposition in soluble copolymers: A, linear; B, branched—long branches; C, branched—branches protruding from branches give a dendritic structure.

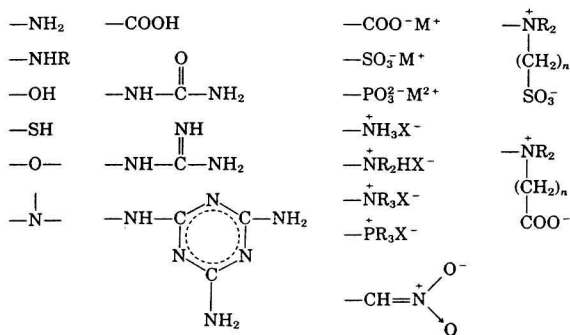
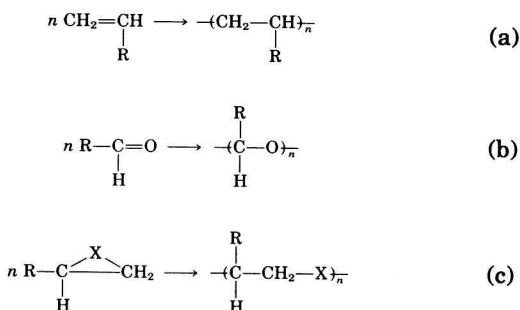


Figure 2. Functional groups imparting water solubility.

can be obtained by carefully controlling monomer reactivity, concentration, order of addition, and reaction conditions.

Step growth condensation reactions may be conducted in solution, bulk, interfacially, microheterogeneously, or on solid supports. Often active esters are employed at low temperatures to obtain water-soluble polyesters or polyamides. Sequential addition of protected monomers onto polymer supports is employed for preparation of synthetic polypeptides, polynucleotides, and polysaccharides.

Scheme 1 illustrates the major mechanisms for preparation of commercial synthetic water-soluble polymers by direct chain growth or ring opening of functionalized alkenes, carbonyl monomers, or strained ring systems. Initiation may be accomplished free radically, anionically, cationically, or by coordination catalysis depending on monomer structure.



Scheme 1. Major synthetic pathways for preparing water-soluble polymers.

A number of synthetic procedures utilizing aqueous solutions, dispersions, suspensions, or emulsions are particularly useful for commercial production. For example, water-soluble monomers are easily copolymerized in water-in-oil emulsions or suspensions. For copolymerization of hydrophobic and hydrophilic monomers, microemulsions or aqueous solutions of high surfactant concentration are often required. The large number of variables that control polymer microstructure and reaction kinetics are discussed in subsequent chapters of this book.

Hydrodynamic Volume

Solution behavior of polymers can best be predicted by considering chemical structure and hydrodynamic volume (HDV) or that volume occupied by the solvated chain. Theoretical attempts to relate dimensions of macromolecular chains in solution to repeating unit structure were pioneered by Flory (1). Of particular importance to the extension of such theories to aqueous polyelectrolytes were the contributions of Morawetz (2), Tanford (3), and Strauss (4). Some of the conceptually simple aspects of these theories, useful to the organic chemist in tailoring polymers, are discussed below.

Initially, a freely jointed chain was described having an end-to-end distance, r , related to the number of bonds, n , and the length of each bond, l , by Equation 1, Figure 3a. Valence bond angle (θ) and conformational angle (ϕ) restrictions were introduced (Equation 2, Figure 3b) to impose directionality to the chain. Often the latter terms are replaced with a stiffness parameter.

Despite the chain stiffening introduced by valence bond and conformational restrictions, Equation 2 greatly underestimates the experimentally determined end-to-end distances even for uncharged polymers. In a macromolecular chain, additional expansion is predicted since segments cannot spatially occupy sites filled by other segments. Additionally in thermodynamically "good" solvents, the chain is markedly expanded. Reasonably good approximations of the end-to-end distance can be obtained by including an expansion factor (α) shown in Equation 3.

In addition to the excluded volume and solvation effects, longer range molecular interactions, charge-charge repulsions (or attractions), hydrogen bonding, etc., may contribute to the value of α . A number of theoretical models (2,3) incorporate additional terms to specifically deal with both short- and long-range repulsive effects schematically shown in Figure 3c. Recently, a number of powerful computer programs have been developed to spatially represent macromolecules in solution. In some limited cases—most frequently well behaved homopolymers of low molecular weight in organic solvents—models agree with experimental observations. Water-soluble polymers, particularly those with microheterogeneous phase behavior, have not been successfully modeled to date.

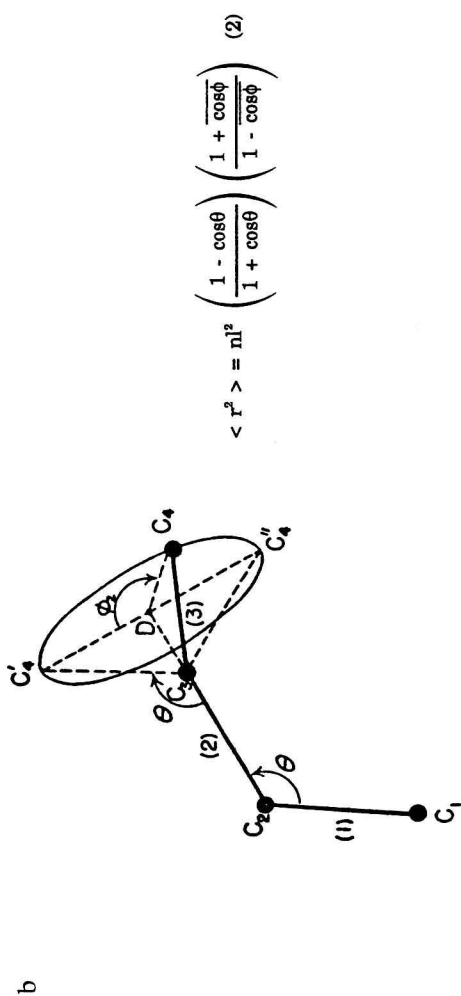
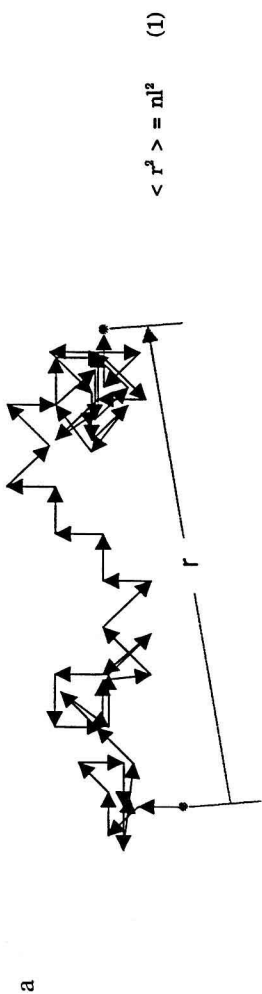
Synthetic Strategies for Controlling HDV

An examination of Equation 3 reveals potential synthetic approaches for increasing average end-to-end distance and thus HDV of macromolecules. The number of bonds, n , can be increased by increasing the degree of polymerization (DP). Choice of appropriate monomers and mechanisms (free radical, anionic, cationic, coordination, or template) can lead to high DP. Step growth polymers usually have relatively low DP and rely on other interactions for reasonable values of HDV. Notable exceptions are found in biopolymers.

The effective bond length, l , may be increased by appropriate choice of monomers. Note that r varies directly with l , and with $n^{0.5}$ in Equation 3. Introduction of cyclic rings (polysaccharides), double or triple bonds increase rigidity by effecting valence bond angle (θ) changes. Likewise, rotational bond angles (ϕ) might be changed by introducing steric bulk along the backbone. This must, however, be accomplished without compromising DP and thus n . Temperature, of course, determines the availability of various rotational states (i.e., the number of trans conformations) and thus HDV.

Other effective ways to increase hydrodynamic volume are shown in Figure 4. Adjacent mer units may act in concert if associated by hydrogen bonding (partially hydrolyzed acrylamide) or ionic charge interactions to yield longer effective bond lengths with restrictive rotations. In some instances configurational restrictions lead to chain-stiffening by helix formation (polynucleotides and polypeptides).

Finally, chain expansion may be realized by increasing the polymer solvent interaction or the "goodness" of the solvent and by introduction of like charges along or pendent to the macromolecular backbone. Extremely large HDV's are attainable for flexible polyelectrolytes in deionized water; addition of simple electrolytes dramatically reduces HDV. This typical polyelectrolyte behavior and the contrasting behavior of polyampholytes will be addressed later.



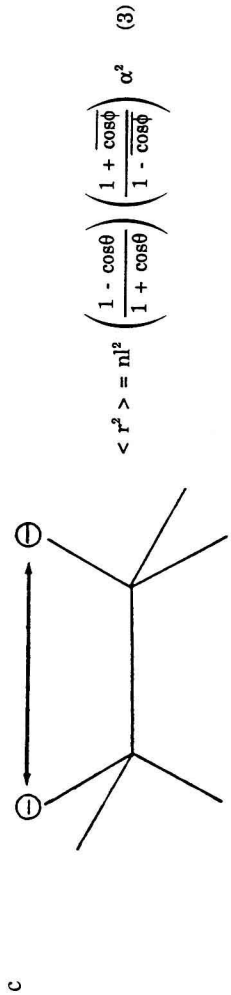


Figure 3. (a) Vectorial representation in two dimensions of a freely jointed chain. A random walk of fifty steps. (b) Spatial representation of a simple singly bonded carbon chain. (c) Intramolecular charge-charge repulsion.