Nr 4 (227—292) KWIECIEŃ 2001 Tom XLVI

POLIMERY

MIESIĘCZNIK POŚWIĘCONY CHEMII, TECHNOLOGII I PRZETWÓRSTWU POLIMERÓW

LARS-ÅKE LINDÉN*), JULITA JAKUBIAK**)

Three-dimensional (3D) photopolymerization in the stereolitography

Part III. MEDICAL APPLICATIONS OF LASER-INDUCED PHOTOPOLYMERIZATION AND 3D STEREOLITHOGRAPHY***)

Summary — A review with 40 references covering laser-induced photopolymerization in microsurgery, *e.g.*, *in vivo* repair of an injured knee (Fig. 1) and *in vivo* repair or reinforcement of tendon ligaments (Fig. 2); applications of 3D CAD—CAM in surgery to produce high-resolution images of internal body parts *via* computer-assisted tomography and magnetic resonance imaging interfaced with rapid prototyping and manufacturing systems and stereolithographic equipment (Figs. 3—5); and design and manufacturing of orthopaedic implants [involving 3D CAD—CAM systems (Figs. 7, 8)]. The applications of photopolymerized resin composites as implants pose severe biological problems and require more intensive studies to achieve a significant progress.
Key words: three-dimensional photopolymerization in stereolithography, laser-induced photopolymerization and 3D stereolithography applications in microsurgery.

During the recent decade laser polymerization has found wide application in photocuring [3—5]. The possibility of manufacturing accurate and fast medical models by 3D photopolymerization opens new perspectives in the manufacturing of medical prototypes (*e.g.* endoprostheses). Prof. D. C. Neckers (Center for Photochemical Sciences, Bowling Green State University, Bowling Green, OH, USA) pioneered in the use of stereolithography in medical imaging. He has developed, in collaboration with Prof. L. T. Andrews (Director of Imaging Analysis Laboratory, Medical College of Ohio, Toledo, OH, USA), the first use of photopolymerization in 3D models for diagnosis and surgical planning. Prof. K. Kędzior (Institute of Aeronautics and Applied Mechanics, Warsaw University of Technology, Warsaw, Poland) together with Prof. K. Skalski (Institute of Mechanics and Design, Faculty of Production Engineering, Warsaw University of Technology, Warsaw, Poland) have applied stereolithography in the medical field. The Medical Imaging Division, Department of Radiological Sciences, University of California, Los Angeles, USA, can supply technical information on medical applications of computer-assisted tomography.

Three dimensional (3D) photopolymerization (stereolithography) linking the computer models (Computer Aided Design (CAD)) with Computer Aided Manufacturing (CAM) processes [1, 2] has already been widely used in medicine.

*) Polymer Research Group, Department of Dental Biomaterials Science, Karolinska Institute, Box 4064, 141 04 Huddinge (Stockholm), Sweden.

**) Department of Chemistry, Jagiellonian University, Ingardena 3, 30-060 Cracow, Poland. To whom all correspondence should be addressed.

***) Part I see [1]. Part II see [2].

LASER PHOTOPOLYMERIZATION IN MICROSURGERY

Laser photopolymerization in microsurgery can be exemplified by two cases [6]:

— Repair of a damaged joint (such as knee) (Fig. 1): a biocompatible monomer is photopolymerized by laser radiation directed with a fiber optic onto the surface of the damaged joint. A repaired surface could be generated by polymerizing as many layers of the material as required over the affected area.

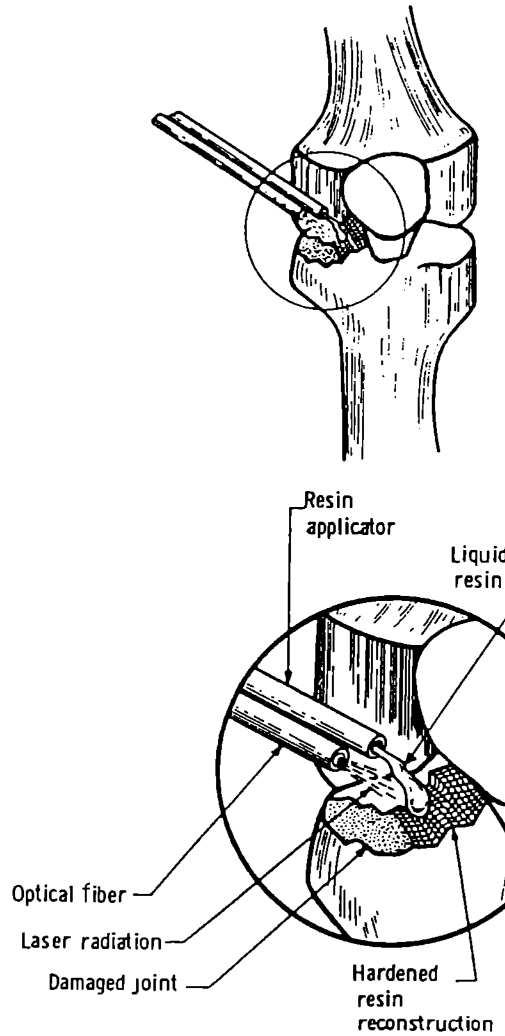

Fig. 1. Repair of a damaged joint surface by laser-induced photopolymerization [6]

— Repair or reinforcement of tendon ligaments (Fig. 2): a web of an appropriate reinforcing material, *e.g.*, a carbon fiber web, is used as a matrix to provide additional strength [7]. By varying the type and distribution of the reinforcing phase in the composite, it is possible to achieve a wide range of mechanical and biological properties, and hence to optimize the structure of the implant and its interaction with the surrounding tissues. A resin composite of different monomers is thus ap-

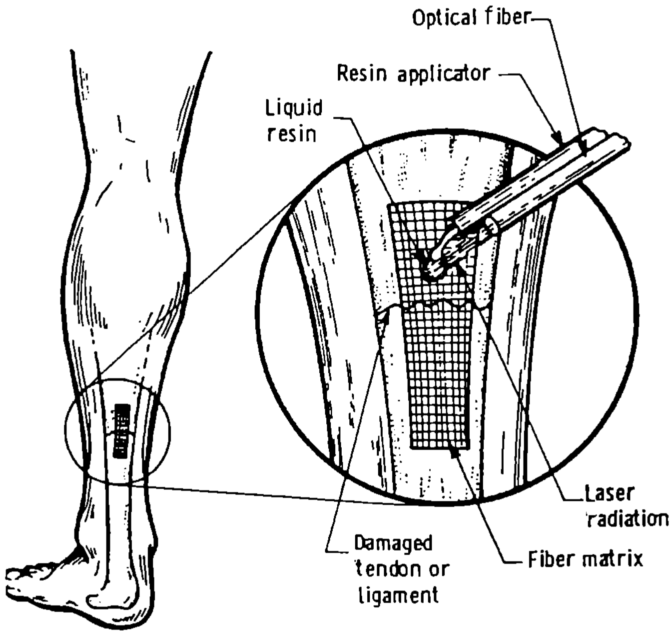

Fig. 2. Repair of a tendon using laser-induced photopolymerization [6]

plied in layers and photopolymerized by laser radiation from a fiber optic device. An appropriate polymer, which would bond strongly to the existing tendon, ligament, and bone tissue, would allow the repair to take place without sutures, staples, or other attachment devices.

MEDICAL APPLICATIONS OF 3D CAD—CAM IN SURGERY

The capability of manufacturing stereolithographic models directly from medical images has enabled prototyping to be introduced into surgery [8, 9]. Computer Assisted Tomography (CAT) and Magnetic Resonance Imaging (MRI) give high resolution images of internal structures of human body. The 3D scanning techniques together with powerful software and hardware, allow us to represent these data in three dimensions: shaded images, chine views, virtual reality and holograms. A special purpose software has been developed to inter-

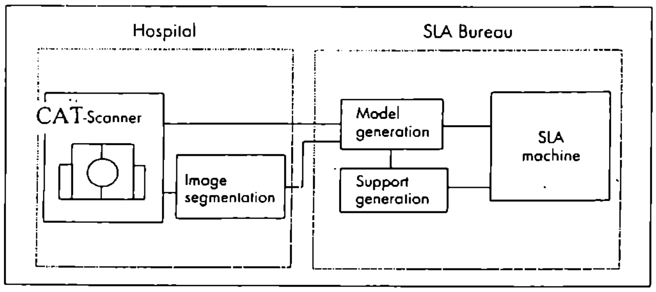

Fig. 3. Scheme of the connection between a hospital and a SLA Bureau [14]

face both the CAT and the MRI scanners directly to the Rapid Prototyping and Manufacturing (RPM) systems and to Stereo Lithography Apparatus (SLA) (Fig. 3).

The ultimate 3D representation, a solid model, is very helpful in the preparations for complex surgery [8—27]. These models can be used for three purposes [8, 14]:

— A 3D model can serve as a hard copy of the data set and provide both visual and tactile documentation for diagnosis, therapy planning and didactic purposes (Fig. 4).

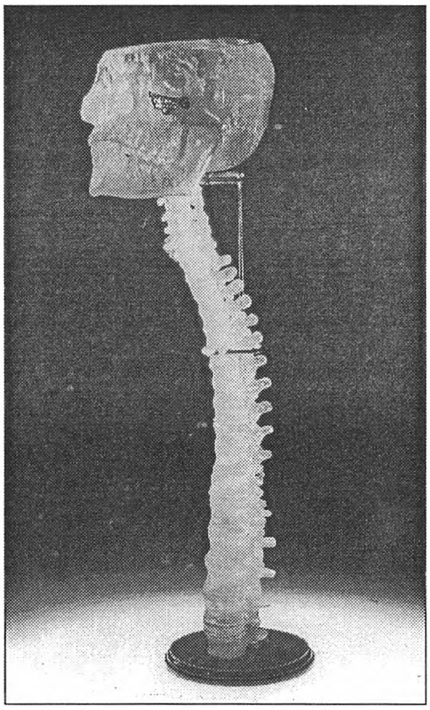

Fig. 4. The 3D SL model for didactic purposes (provided by Corporate Headquarters 3D Systems, Inc., USA)

— 3D models can be very useful in the planning of complex surgery, which may involve simulations on a 3D model. For some models, optical transparency is very important. An example would be the ability to see the mandibular channel in the lower jaw. However, for other applications, transparency is not desirable, because it may provide misleading visual effects.

— When an accurate 3D model of an existing structure is available, the replacing prostheses are much easier to design. The model can serve as a negative from which the implant is manually generated prior to surgery, or it can serve directly as a master for the implant. Figure 5 shows the steps in the creation of a custom fitted skull prosthesis [9, 27, 28]. Correction and rebuilding of some bone structures, by using stereolithographic models, allow us to avoid time consuming "fitting and chipping" procedures, because the surgeon already knows exactly the shape and the size involved before the surgery even starts. Stabilization of the bony parts is very accurate, and the surgeon can thereby proceed directly to the fixation procedure [14].

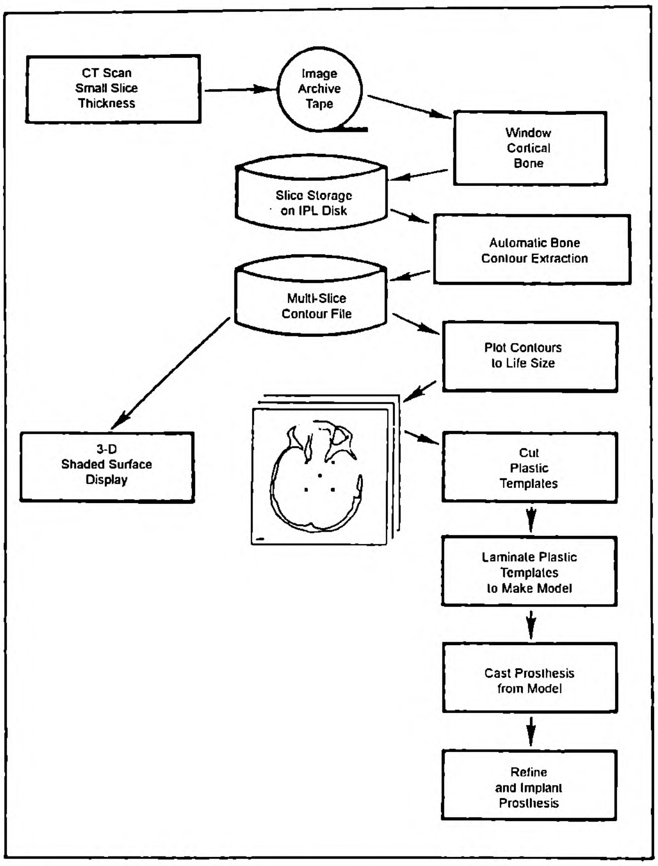

Fig. 5. Steps used in the creation of a custom fitted skull prosthesis [9]

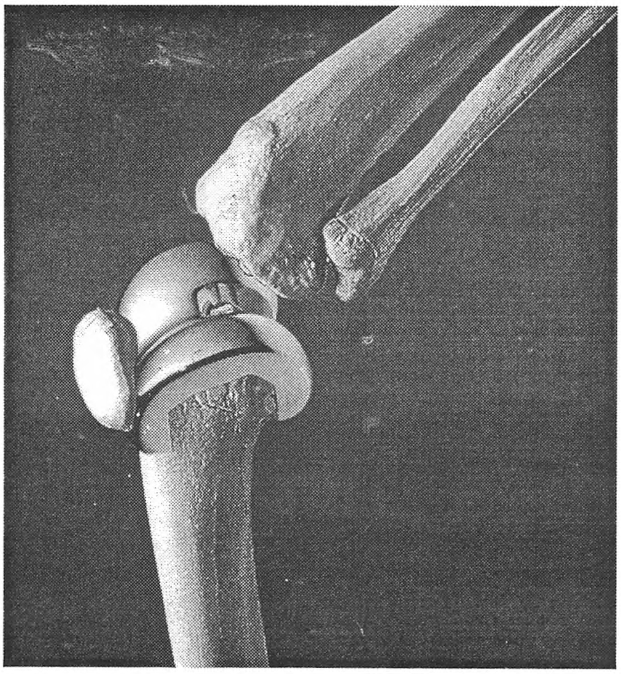

Fig. 6. The 3D SL shoulder prototype (provided by Corporate Headquarters 3D Systems, Inc., USA)

— The medical models are extremely useful as visualization tools for surgical rehearsal as well as in preparing implants. Currently, 3D SL generated medical models are mostly used in maxillo-facial, cranio-facial and oral surgery [22, 25, 27, 29]. However, they also have a limited use in conjunction with spinal, hand, foot, and hip surgery [30]. In Fig. 6 is shown a 3D SL shoulder prototype.

DESIGN AND MANUFACTURING OF ORTHOPAEDIC IMPLANTS BY 3D CAD—CAM SYSTEMS

Degenerative and arthritic tissues (joint diseases) often result in very painful and/or non-functional joint movements. Custom-made implants are necessary in situations when off-the-shelf standard size implants are not suitable. A custom-made implant is produced on a prescription basis and is unique for each patient in cases involving bone deformity or loss. The surgeon and the custom engineer work together using either patient X-rays or CAT scans (Fig. 7) to design and develop the implant or to study actual bone geometry as a reference (Fig. 8) [30—33]. In the 3D device a model prototype is then obtained, which can be sent to the surgeon for review and approval.

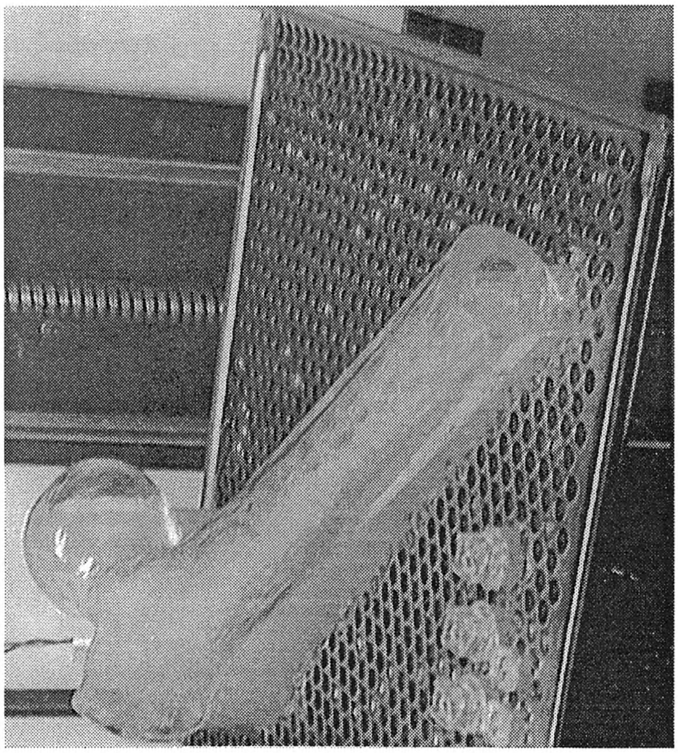

Fig. 8. Bone model made after CAT-scan (provided by Prof. K. Skalski, Institute of Mechanics and Design, Faculty of Production Engineering, Warsaw University of Technology, Warsaw, Poland)

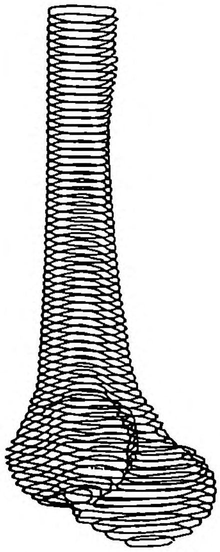

Fig. 7. CAT scan data [30]

BIOLOGICAL DISADVANTAGES OF APPLYING PHOTOPOLYMERIZED POLYMER RESIN COMPOSITES

The main problems in photopolymerization are the limited depth of polymerization (*cf.* [1]) and the low monomer conversion efficiency. For the latter, different factors can be responsible:

— Low radical concentration, low radical initiation effectiveness, and sample thickness [34], *e.g.*, increasing the photo-initiator concentration from 1% to 5 % can decrease the amount of unreacted monomer molecules from 22 % to 8 % [35];

— Increase in viscosity during the propagation and reaching the gel point, which can restrict the mobility of the propagating radicals [36];

— Termination reactions;

— Filler fractions that are too high, limit the penetration of light to the deeper layers of the samples.

Incomplete photocuring in the inner parts of implants may cause large internal stresses, which have injurious effects on the mechanical properties. At a low degree of monomer conversion (<90%), the final photopolymerized implant contains a significant amount of unreacted monomer. Many (meth)acrylic monomers show toxicological and pharmacological actions [37, 38] as well as chronic effects such as carcinogenicity, mutagenicity, and teratogenicity. These monomers effectively reduce the defense potential of the immune system, either by cytotoxic effects or by a more specific immune mechanism [39].

Poly(methacrylates) can cause limited local death of the bone tissue at the site of implantation owing to the methacrylate monomer leaching out of the material cured *in situ* [40].

Cleaning and sterilizing the final 3D implant obtained during photopolymerization may require special processes. Polymer materials absorb organic solvents and this may result in damaging of the implant or subsequent leaching out of toxic monomers and photoinitiators (especially amines). Many existing methods of sterilization involving gamma irradiation or heating to elevated temperatures (for example in an autoclave) may also damage polymeric composite implants.

REFERENCES

1. Jakubiak J., Rabek. J. F.: *Polimery* 2000, **45**, 759.
2. Jakubiak J., Rabek J. F.: *Polimery* 2001, **46**, 164.
3. Decker C., Elzaouk B. in: "Current Trends in Polymer Photochemistry" (Eds., Allen N. S., Edge M., Bellobono I. R.), Elis Howard, New York, 1995, p. 130.
4. Decker C., Fouassier J. P. in: "Radiation Curing in Polymer Science and Technology", Vol. III "Technology and Applications" (Eds., Fouassier J. P., Rabek J. F.), Elsevier Applied Science, London, 1993, p. 1.
5. Braüchle C., Wild U. P., Burland D. M., Bjorklund G. C., Alvarez D. C.: *IBM Res. Dev.*1982, **26**, 1982.
6. Castle P. M., Sadhir R. K. in: "Radiation Curing in Polymer Science and Technology" Vol. III (Eds., Fouassier J. P., Rabek J. F.), CRC Press, Boca Raton 1993, p. 37.
7. Evans S. L., Gregson P. J.: *Biomaterials* 1998, **19**, 1329.
8. Vancraen W., Swaelens B.: Proc. RadTech '95 Europe, Maastricht, The Netherlands, 1995, p. 624.
9. Mankovich N. J, Woodruff T. J., Beumer J. III: SPIE, Vol. 535, Application of Optical Instrumentation in Medicine XIII, 1985, p. 314.
10. Alberti C.: *Br. J. Radiol.* 1980 (March), 132.
11. Vannier M. V., March J. L., Gado M. H.: *Electromedica* 1983, **51**, 122.
12. Brix F., Lambrecht J. T.: *Fortsch. Kiefer & Gesicht-Chirurgie* 1987, **32**, 74.
13. Mankovich N. J., Cheesman A. M., Stoker N. G.: *J. Digit Imaging* 1990 (Aug.), 3.
14. Swaelens B.: in "Stereolithography and Other RP&M Technologies: from Rapid Prototyping to Rapid Tooling" (Ed., Jacobs P. F.), Society Manufacturing Engineers, Deaborn, 1996, p. 339.
15. Gerard H., Andre J. C., Mallet J. L.: *Eur. Microscopy Analysis* 1993, 23.
16. Frohberg U., Haase L.: *Rev. Stomatol. Chir. Maxillofac.* 1995, **94**, 33.
17. Lambrecht J. T.: "3D Modelling Technology in ENT and Maxillofacial Surgery", Quintessence Books, 1995.
18. Eppley B. L., Sadove A. M.: *J. Craniofacial Surg.* 1988, **9**, 548.
19. Mole C.: *Actual Biomat.* 1993, **2**, 281.
20. Mole C., Gerard H., Della Malva R., Mallet J. L., Corbel S., Miller N., Penaud J.: *Actual Odont. Stomatol.* 1993, **181**, 127.
21. Mole C., Chassagne J. F., Corbel S., Gerard H., Mallet J. L.: in "Actualites en Biomateriaux" (Eds., de Mainard D., Merle M., Delagoutte J. P., Louis J. P.), Romillat Ed., Paris, 1998, p. 483.
22. Bill J. S., Reuther J. F., Dittmann W., Kübler N., Meier J. L., Pistner H., Wittenberg G.: *Int. J. Oral Maxillofac. Surg.* 1995, **24**, 98.
23. Pieper S. D., Laub P. D., Rosen J. M.: *Plast. Reconstr. Surg.* 1995, **96**, 1100.
24. Boyssie J. F., Treil J., Madrid C., Boussie S., Duran D.: *Medicine Buccale* 1996, **2**, 7.
25. Eufinger H., Wehmöller M., Machtens E., Heuser L., Harders A., Kruse D.: *J. Cranio-maxillofac. Surg.* 1995, **23**, 175.
26. Wehmöller M., Eufinger H., Kruse D., Massberg W.: *Int. J. Oral Maxillofac. Surg.* 1995, **24**, 90.
27. Chassagne J. F., Corbel S., Gimenz F., Chassagne S., Gerard H.: *Ann. Chirurgie Plast. Esthetique* 1999, **44**, 515.
28. Eufinger H., Wehmöller M.: *Int. J. Oral Maxillofac. Surg.* 1995, **24**, 104.
29. Santler G., Kärcher H., Ruda C.: *J. Cranio-maxillofac. Surg.* 1998, **26**, 11.
30. Trimmer D. G.: in "Rapid Prototyping & Manufacturing" (Ed., Jacobs P. F.), Society Manufacturing Engineers, Deaborn, 1992, p. 381.
31. Dietrich M., Kędzior K., Skalski K.: *J. Theor. Appl. Mechanics* 1999, **37**, 481.
32. Werner A., Skalski K., Świeszkowski W., Plewicki J.: *Acta of Bioeng. Biomechanics* 1991, **1**, 547.
33. Bossak M., Skalski K., Werner A.: Proc. Intern. Conf. Ergonomics for People with Disabilities, Łódź, 1999, p. 21.
34. Guthrie J., Jeganathan M. B., Otterbrun M. S., Woods J.: *Polym. Bull.* 1986, **15**, 51.
35. Decker C., Mousa K.: *Makromol. Chem.* 1990, **191**, 963.
36. Jakubiak J., Rabek J. F.: *Polimery* 2000, **45**, 659.
37. Revell P. A., George M., Braden M., Freeman M. A. R.: *J. Mater. Sci. Mater. Med.* 1992, **3**, 84.
38. Mir G. N., Lawrence W. H., Autian J.: *J. Pharm. Sci.* 1973, **62**, 778.
39. Rathbun M. A., Hanks C. T., Filisko F. E.: *J. Biomed. Mater. Res.* 1991, **25**, 443.
40. Revell P. A., Braden M., Freeman M. A. R.: *Biomaterials* 1998, **19**, 1579.

Received 3 III 2000.