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Tribology and Biophysics of Artificial Joints

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Aims & Scope
The Tribology Book Series is well established as a major and seminal archival source for definitive books on the subject of classical tribology. The scope of the Series has been widened to include other facets of the now-recognised and expanding topic of Interface Engineering.

The expanded content will now include:
● colloid and multiphase systems; ● rheology; ● colloids; ● tribology and erosion; ● processing systems; ● machining; ● interfaces and adhesion; as well as the classical tribology content which will continue to include ● friction; contact damage; ● lubrication; and ● wear at all length scales.

PREFACE

The present book is devoted to endoprostheses of joints, i.e. artificial joints implanted into the human body. Available in literature information on structural endoprosthetic materials complying with the requirements of biocompatibility and wear resistance is reviewed in this book and a retrospective analysis of modern joint endoprosthetic designs is presented. Data on clinical aspects of endoprosthetics are cited. Along with biological methods the approaches of genetic engineering are paid attention to as promising techniques of designing bone and cartilage transplants. Tribological mechanisms of operation *in vivo* of the endoprosthesis are examined as opposed to the natural joint functioning. The analysis is presented of endoprostheses removed at revision operations and tribological test procedures are characterized.

The traditional designs of artificial joints are known to embody the fundamental ideas advanced in the 1960-ies by an English orthopedist J. Charnley and resemble much machine members that are insufficiently adapted for operation in human organisms. The authors put forward a concept on simulation of biological functions of the bone and cartilage tissue, and bioelectret potentials of natural joints in joint endoprostheses. Information is given on developed by the present authors artificial cartilage based on high-molecular weight polyethylene; its structural, physico-mechanical, tribological and medico-biological characteristics are expounded. Experimental evidences obtained in the course of investigations visualize that blood and synovia exhibit spectra of the thermally stimulated current without any electrical treatment. A principal way of improving lubrication of joint endoprostheses via a constant electric (electret) or magnetic field is justified. Novel joint endoprosthesis designs realizing the established tribological and biophysical regularities are described. A forecast of contemporary trends in joint endoprosthetics is set forth.

The book is addressed to specialists in orthopedy, biophysics, immunology and engineers engaged in developing artificial joints.

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LIST OF ABBREVIATIONS

AAOS – American Association of Orthopaedic Surgeons
BMI – body mass index
CAD – computer-aided design
CAM – computer-aided manufacturing
CART – Clinical and Radiographic Terminology
CITO – Central Institute of Traumatology and Orthopedy named after N.N. Priorov (Russia)
CMC – carboxymethyl cellulose
COG – Children's Oncology Group (USA)
COSSG – Cooperative Osteosarcoma Study Group
CT – computer tomography
DEL – double electrical layer
DGOT – Deutshe Gesellschaft fur Orthopedie und Traumatologie
DNA – deoxyribonucleic acid
DTA – differential thermal analysis
EOI – European Osteosarcoma Intergroup
HDPE – high density polyethylene
HUA – hyaluronic acid
ICNIRP – International Commission on Non-ionizing Radiation Protection
IDES – International Documentation and Evaluation System
MCI – morphological cortical index
MDA - Medical Device Agency (UK)
MF – medicinal form
MS – medicinal substance
MTS – macromolecular therapeutic system
MVO – Medical Vaseline oil
NAPM – non-steroid antiphlogistic medications
PE – polyethylene
PEEK – polyether-etheroketone
PETF – polyethyleneterephthalate
PMMA – polymethyl methacrylate
POM – polyoxymethylene
PTFE – polytetrafluoroethylene
PVA – polyvinyl alcohol
PTFCE – polytrifluorochlorethylene
RR – reinforcement ring
RSA – radiographic spectral analysis
SEDICO – Secure Data Integration Concept
SEM – scanning electron microscopy
SICOT – Scientific International Council of Orthopaedics and Traumatology
SSG – Scandinavian Sarcoma Group

TGF – transforming growth factor
THA – total hip arthroplasty
TSC – thermally stimulated current
UHMWPE – ultrahigh-molecular weight polyethylene
WHO – World Health Organization
ZCP – zero charge point

INTRODUCTION

Endoprostheses are implanted into the human organism mechanical appliances that replace lacking organs or parts of the body. They have come into our life as a magnificent achievement of the mankind comparable to the development of the ocean or space exploration. Not many novelties of modern medicine can stand on a par with endoprosthetics in raising quality of human life. Today endoprostheses of almost all organs have found application in clinical medicine (Fig. 1).

Endoprosthetics of joints is considered as a most efficient method of recovering mobility of joints by their partial or total replacement by artificial components. More than 800,000 endoprosthetic operations on different joints are made in the world yearly [1]. This figure may be much higher since according to the World Association of Health Protection there is an objective necessity in endoprosthetics of joints per each thousand of the population [2]. This fact underlines global character of endoprosthetics of the present day.

The production of joint endoprostheses is a specialized science intensive commercial sphere. The materials used for them should strictly meet a series of requirements, namely chemical inertness, biological compatibility, admissible amount of impurities and so on [3, 4]. Endoprostheses of joints are related as a rule to high-precision products whose friction surfaces are machined very thoroughly [5]. Tolerances are also paid much attention to along with a given accuracy of the conjunction [6]. Members of endoprostheses manufactured at different enterprises should conform to international standards and be interchangeable [5, 6]. The production process of endoprostheses employs high-accuracy machine tools, automatic machines, robots and repeated control of process regimes. The rooms where joint endoprostheses are manufactured, packed and sterilized should meet strict sanitary and hygienic norms [7]. The degree of biological and physical contamination of air in such rooms can be characterized by the term "*clean room*".

Endoprosthetics of joints is made in the course of surgical operations by highly qualified orthopaedists, traumatologists in specifically equipped operating rooms with available antibiotics of a wide spectrum, preparations for prophylactics of thromboembolic complications and so on. As a result, endoprosthetics of joints has isolated recently into an independent trend in operative orthopaedics. A tendency has been also traced at the end of the 20th century of conducting endoprosthetic operations in specialized regional centres.

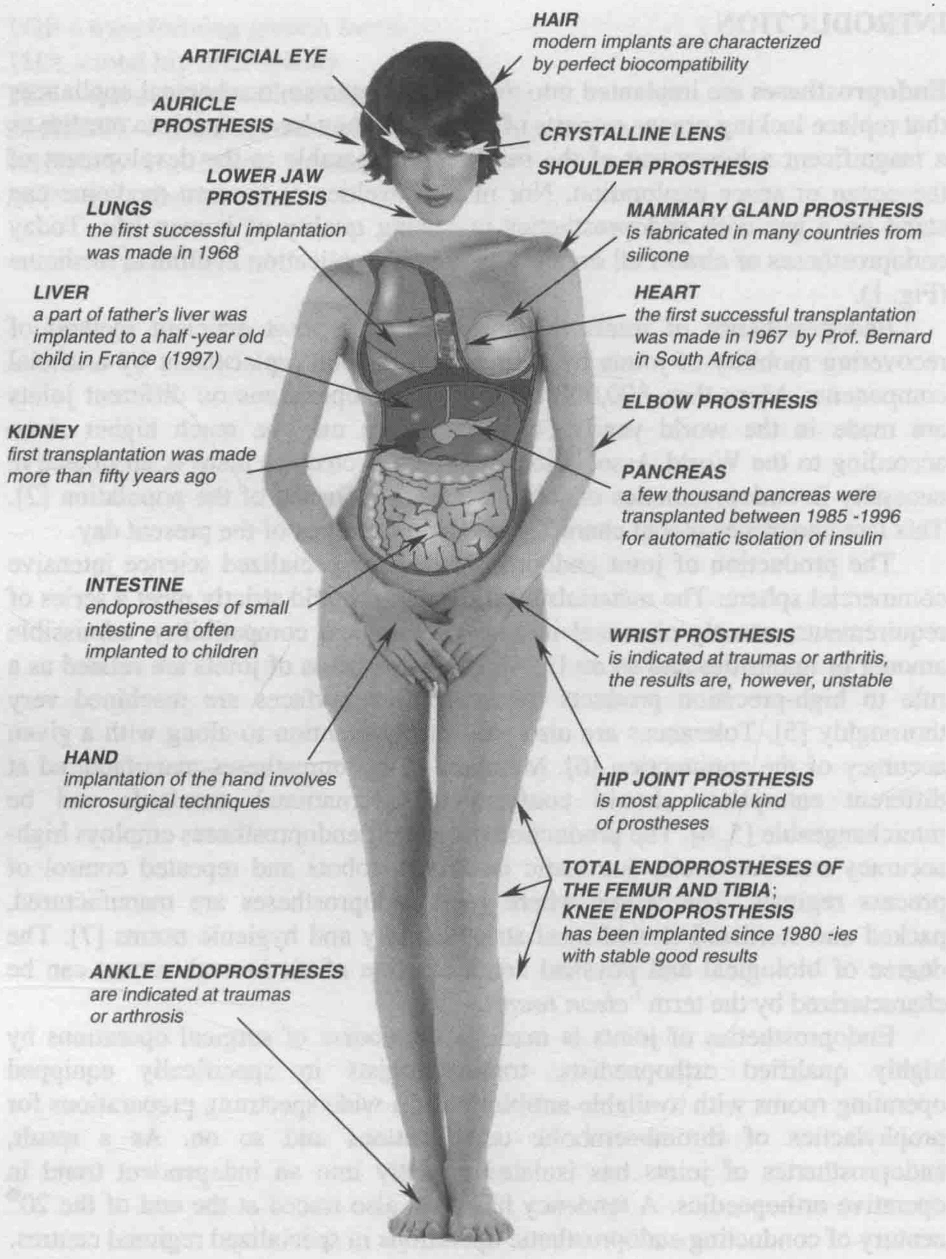

Fig. 1. Potentialities of reconstruction surgery

Within the first years after the endoprosthetic operation the results are commonly good and excellent. Medical observations show that with time there arises a necessity in substitution of the endoprosthesis or its components. The data on the terms of revision operations on e.g. the hip are contradictory [8-10], and the ratio of the initial to revision operations has a dangerous tendency to grow 4:1 and even 3:1. This situation is a subject of anxiety for the developers of endoprostheses as well as orthopaedists and traumatologists.

Human joints consist of biological tissues that are less strong than the modern structural materials of endoprostheses but surpass them much in wear resistance. Most apparent difference of the endoprosthesis from a natural joint is in fundamentally different lubrication mechanisms [11]. The key role in joint lubrication is played by the cartilage, which along with the antifrictional material fulfils the function of a porous reservoir for the synovia. There is no such an element in traditional endoprostheses designs. The comparison of the designs, lubrication mechanisms and functioning of natural joints to endoprostheses suggests that the latter resemble machine joint insufficiently adjusted for operation in human organism.

The analysis of removed during revision operations endoprostheses has proved that the chief problem limiting their stability and durability is inadequate wear resistance of the friction joints. Since this problem is found at the junction of such sciences as medicine, biophysics, triboengineering, materials science, and etc., its solution requires close collaboration of orthopaedists, traumatologists, technicians, biomechanics, immunologists and other professionals.

The present authors have pursued the aim to challenge specialists of different spheres interested in endoprosthetics and its rapid development. Just in cooperative work a new generation of endoprostheses can be created to perform not only mechanical but some biological functions as well, bring them close to natural tissues by their physico-chemical structure and so on. This noble aim is undoubtedly attainable from the standpoint of modern achievements in science and engineering. It requires attraction of the knowledge accumulated in biology, medicine, along with biophysical regularities of functioning of the locomotor apparatus, and high techniques of material preparation and processing.

The book contains both experimental and clinical results obtained at V.A. Belyi Metal-Polymer Research Institute of National AS of Belarus (MPRI), Belarussian Research Institute of Traumatology and Orthopaedics (BelRITO) and Gomel State Medical University.

The authors are grateful to Yu.M. Pleskachevsky and N.K. Myshkin, the former and the present directors of MPRI – for their meticulous attention to this work, E.D. Beloenko, Director of BelRITO, S.I. Boltrukevich, Head of Grodno Regional Traumatology-Orthopedic Center and Clinics, Zh.V. Kadolich, researcher of MPRI – for creative participation in elaboration of the ideas, V.A. Struk, Head of Chair of Grodno State University – for the ideological support and realizing of new types of endoprostheses in practice, L.S. Pushkina, I.I. Kekukh, E.A. Sementovskaya and S.V. Zotov, collaborators of MPRI – for invaluable contribution in preparation of this work. We are sincerely grateful to Professor of the University of Leeds, Duncan Dowson whose fruitful ideas assisted in the development of the artificial cartilage.

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Chapter 1. ARTHROLOGY AND JOINT ENDOPROSTHETICS

Arthrology (*arthrologia*) is a section of medicine studying joints and their diseases. Modern arthrology is closely interrelated with endoprosthetics as one of most efficient means of treating joint pathologies that result from traumas or degenerative-dystrophic, inflammatory, oncological or other injuries. This intimate interdependence between arthrology and endoprosthetics is disclosed in the present chapter. A brief account of human joints and their pathology precedes the discussion on the main clinical indications for joint replacement. It is followed by the analysis of symptoms for surgical treatment, preoperative planning and delayed results of joint endoprosthetics. Named problems are described in evolution and estimated from the viewpoint of professionals in this field in the prehistory essay.

1.1 HUMAN JOINTS AND THEIR PATHOLOGY

A simplified anatomic scheme of a human joint illustrated in Fig. 1.1 shows the principal structural elements with articulating surfaces covered by a hyaline cartilage and enclosed in a joint capsule. The capsule is formed of a fibrous shell covered by a synovial backing on the inside and filled with a synovial fluid, which serves as a lubricating medium. The hyaline cartilage thickness as about 0.2–6.0 mm depending on the distribution of loads over the contact surface [1].

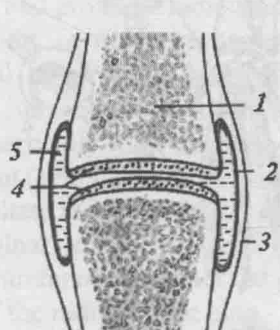

Fig. 1.1. Anatomic structure of joint: 1 – bone, 2 – synovial backing, 3 – fibrous capsule, 4 – joint cartilage, 5 – synovial fluid

The joint cartilage consists of chondrocytes and a collagen backing. The chondrocytes are oval or spherical cartilage cells having small processes and enclosed in the collagen cavities (lacunas).

The physico-chemical and contact interactions of the structural elements create an optimum biophysical basis for the exchange processes between the joint cavity and blood vessel. These interactions are intrinsic for the normal long-term functioning of joints.

The outline of articulating surfaces complies with geometrical bodies like the cylinder, ellipsoid, sphere, and other (Fig.1.2), which defines the number of axes for articulation and sliding of the joints. The cylindrical configuration makes possible rotation only about a single axis, the ellipsoidal – about two axes, and spherical – about three mutually perpendicular axes. This is why the biomechanical classification of joints envisages their subdivision into a uni-, bi- and triaxial types. The cylindrical and block-shaped joints are related to the uniaxial types (Fig. 1.2, *a*). Ellipsoidal (*b*), saddle-like (*c*), and condylar (a transient from the block to the ellipsoidal form, e.g. the knee) belong to biaxial types of joints. Triaxial joints represent a ball conjugated with a socket whose depth predetermines either a spheroid (shoulder, 3) or a cup-shaped (hip) joint [2].

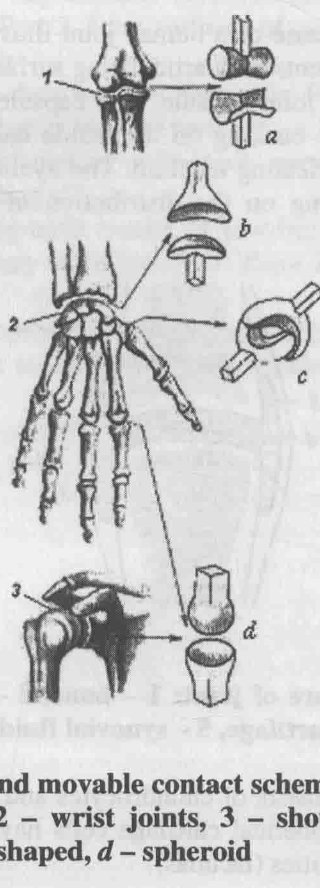

Fig. 1.2. Joints (1–3) and movable contact schemes of articular surfaces (*a*–*d*): 1 – elbow joint, 2 – wrist joints, 3 – shoulder; *a* – block-type, *b* – ellipsoidal, *c* – saddle-shaped, *d* – spheroid