ISSN 1330-3651 (Print), ISSN 1848-6339 (Online)
UDC/UDK 621.7.044.4:666.946]:616.314

DISINTEGRATION OF BONE CEMENT BY CONTINUOUS AND PULSATING WATER JET

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Original scientific paper
The paper deals with the study of using continuous water jet and ultrasonic pulsating water jet for bone cement disintegration. Bone-cement Pallacos R+G (manually mixed) was disintegrated ex-vivo. Mechanical properties of the bone cement were determined by nano-indentation. Factors employed in evaluation were pressure (40, 80, 120) MPa and traverse speed for continuous water jet, pressure (8, 10, 12, 14, 16, 20) MPa and orifice type (flat, circular) for ultrasonic pulsating water jet. Depth penetration *h* (mm) was measured by non-contact optical profilometer MicroProf FRT. Results represent the first step towards feasibility of using effective water jet technique during reimplantation of cemented endoprosthesis, for bone cement removal from femoral canal without heat and mechanical damage of surrounding tissue.

Keywords: *bone cement, disintegration, water jet*

Dezintegracija koštanog cementa pomoću kontinuiranog i pulsirajućeg mlaza vode

Izvorni znanstveni članak
Članak se bavi proučavanjem uporabe kontinuiranog vodenog mlaza i nadzvučnog pulsirajućeg mlaza vode za dezintegraciju koštanog cementa. Koštani cement Pallacos R+G (ručno miješan) dezintegriran je ex-vivo. Mehanička svojstva koštanog cementa određena su pomoću nano-utiskivanja. Faktori u procjeni bili su tlakovi (40, 80, 120) MPa i poprečna brzina kontinuiranog mlaza vode, tlak (8, 10, 12, 14, 16, 20) MPa i tip prigušnice (ravna, kružna) za nadzvučni pulsirajući mlaz vode. Dubina prodiranja *h* (mm) mjerena je bezkontaktnim optičkim profilometerom MicroProf FRT. Rezultati predstavljaju prvi korak ka izvedivosti uporabe učinkovite tehnike vodenog mlaza tijekom reimplantacije cementiranih endoproteza, za uklanjanje koštanog cementa iz bedrenog kanala bez topline i mehaničkog oštećenja okolnog tkiva.

Ključne riječi: *dezintegracija, koštani cement, vodeni mlaz*

1 Introduction

Number of cemented and non-cemented endoprostheses reimplantations is increasing [1, 2]. Effective surgical process of total hip and knee replacement depends on technology [3 ÷ 6]. Problematic issues of artificial joints are wear [7, 8] and corrosion [9], which leads to aseptic failure of endoprostheses [2]. The bio-material disintegration during revision arthroplasty issue is currently an existing problem of more surgeons even in regard to the fact that the bone tissue is a compact and living material [1, 10 ÷ 13]. To make the damaged total cemented endoprosthesis extractable the interface between the bone and bone cement is inevitable to be disturbed [1]. Negative side effects of using classical tools during reimplantation of cemented endoprostheses are distinctive heat and deformation impacts, loosing of biological potential. It is the application of the water jet cutting that offers eventuality of eliminating the negative features of classical tools [14 ÷ 17] and unconventional processes [18-22]. The aim of the study is comparison of continuous and ultrasonic pulsating water jet from the performance point of view during bone cement disintegration. The intention of authors is decreasing the technological level set up, in order to simplify the introduction of water jet technology to orthopaedic field.

2 State of the art analysis

Bone cement removal was studied by many authors [23 ÷ 32]. Many techniques were developed in order to enhance bone cement removal during endoprostheses replacement. The usual methods of removal of bone cement include high-speed drills, chisels, saws, and reamers, which are often associated with fracture or perforation of the femoral shaft [33]. The removal of bone cement from the femoral canal takes a certain amount of time and carries the risk of complications, thus risking bone damage and perhaps even endangering the successful reimplantation of a new prosthesis [1]. Schmidt and Nordman [28] demonstrated experimentally that the milling of bone and bone cement produces acoustic emission waves of different intensity. These waves can be measured by a commercial acoustic emission transducer. This method enables us to control the milling device during the removal of bone cement from deep in the femoral canal, avoiding the serious damage to the bone and thus enabling a new prosthesis to be reimplanted. Ultrasonic devices offer an alternative method of cement removal by converting mechanical vibrations into thermal energy, liquefying the cement. This facilitates selective cement removal, preserves bone, decreases bone perforation risk, and eliminates the need for osteotomy. However, the potential for thermal injury exists. Schwaller and Elke [34] presented an ultrasonic device for rapid cement removal with minimum risk of trauma to the fragile femoral bone. The technique of cement removal with ultrasound is described and problems and risks are addressed. Goldberg et al studied ultrasound basic science, mechanism of action and clinical applications with specific emphasis on methods to limit heat generation. Honl et al. [31] cut 32 specimens of PMMA with a continuous and a pulsating water jet at pressures (40 MPa, 60 MPa) and pulse frequencies (0 Hz, 50 Hz, 250 Hz). They noticed that the pulsating jet had the important advantage over conventional tools for the selective removal of bone cement. With regard to removal selectiveness it is possible to use the water jet with low pressure to disturb the interface created by the bone cement the physical and mechanical properties of which are diametrically different from those of the bone tissue or titanium endoprosthesis. Disintegration of the surface of bone tissues and other biomaterials by high-speed fluid jet represents an issue interfering in several branches of clinical practice [35]. Standard use of continuous fluid jet involves surface disintegration, cutting of various kinds of (bio) materials. It is possible to significantly increase the efficiency of impact of continuous fluid jet by its modulation [36, 37]. Generation of high-frequency pressure pulsations in systems for generation of high-speed water jets represents one of the possibilities of technology efficiency increasing in medical applications for removal of surface layers, cleaning, and volume disintegrations of materials, for instance, bone cement from femoral canal. Above mentioned authors showed path for possible effective removal of bone cement. But there are still unresolved issues such insufficient respect of physical and mechanical or stress and deformation integrity of the system: technological factors – tool – material (mechanical properties).

3 Materials and methods

3.1 Palacos mechanical properties determination

Experiments were realised based on the above defined problems. Commercially available bone cement Palacos R+G® (ZIMMER) which has a broad spectrum covering gram-positive and gram-negative bacteria was used in the study. Bone cement was prepared in strict compliance with manufacturer's instructions by manual mixing. The samples sections for nano-indentation were metallographically polished down to the roughness lower than 0,1 μm. All nano-indentation measurements were performed by nano-indentation tester TTX-NHT (by CSM Instruments, Switzerland). Berkovich pyramid diamond tip was used in simple monotonic mode with maximum loading of 10 mN. Loading and unloading rate was 20 mN/min, the hold time at the maximum was 10 s. The resulting load-penetration depth (*P*–*h*) curves were evaluated according to the analysis of Oliver and Pharr [38]. From the applied load and the corresponding contact area, hardness values can be calculated very precisely.

3.2 Technological condition of experiment

The 2D X-Y cutting table PTV WJ2020-2Z-1xPJ with inclinable cutting head, specially designed for cutting with water and abrasive water jet was used for tests of disintegration of PMMA using continuous water jet (Fig. 1). The water pressure was generated by PTV75-60 pump with two pressure intensifiers (operating pressure of 40 ÷ 415 MPa, max. flow of 7,8 l/min at 415 MPa). Cutting traces were created at pressure p = 40, 80, 120 MPa using nozzle orifice diameter d = 0,1 mm.

Pulsating water jet was used in the second test of disintegration of bone cement samples (Fig. 2). The tests were performed at the Institute of Geonics of the ASCR in Ostrava – Poruba. Technological set up consisted of plunger pump Hammelmann HDP 253 (max. operating pressure of 160 MPa, maximum flow of 67 l/min) and a robot ABB IRB 6640-180//2.55 Master for handling of water jet cutting head. Pulsations were generated by ultrasonic device Ecoson WJ-UG_630-40. Technological conditions of tests are listed in Tab. 1.

Table 1 Experimental set up for pulsating water jet tests

Factors	1	2	3	4	5	6	7	8	9	10	11	12
Pressure p / MPa	8	10	12	14	16	18	20	16	20	12	8	
Orifice type	Circular (MVT)							Flat (Hammelmann)				
Orifice diameter d / mm	0,7 mm							0,8 mm – 10°				
Stand-off z / mm	4											2
Traverse speed v / mm/s	1 mm/s											
Modulation frequency / Hz	41,90 kHz											

Figure 1 Cutting traces after disintegration of Palacos R+G® bone cement by continuous water jet with orifice diameter d = 0,1 mm

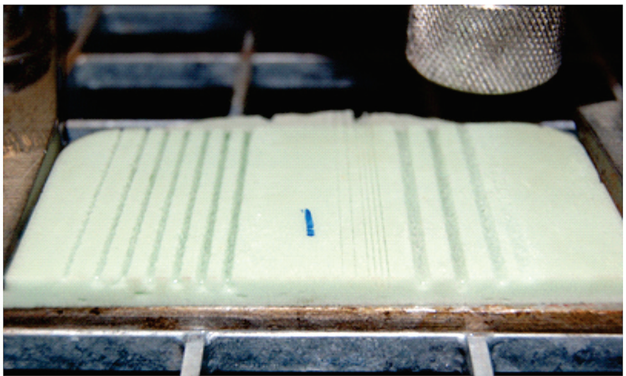

Figure 2 Cutting traces after disintegration of Palacos R+G® bone cement by pulsating and continuous water jet

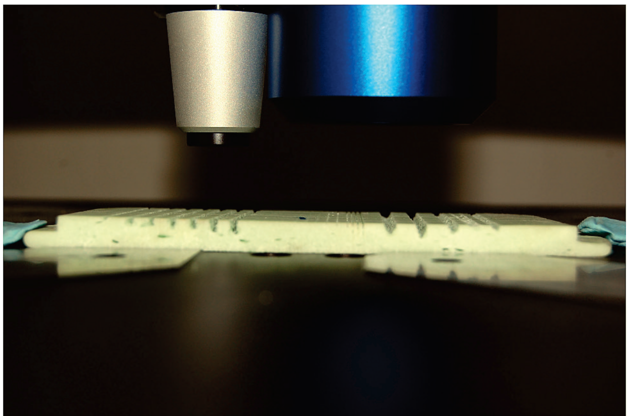

Figure 3 Measurement of disintegrated surface of Palacos R+G® by MicroProf FRT device with the measurement head SEN 000 03

3.3 Measurement

The depth h (mm) of traces created by continuous and pulsating water jet was measured by an optical profilometer MicroProf FRT, using sensor SEN 000 03 (Fig. 3) at the Institute of Geonics AS CR, v.v.i. 3D plot of surface was compiled from lines for every sample with the following measurement parameters: measurement area 25×20 nm, vertical resolution 100/30 nm, accuracy 1 μm, linearity 0,1 %, lateral resolution 6 μm, number of measurement traces 1500, measurement traces distance 13,34 μm.

4 Results and discussion

Results (Fig. 4) present a comprehensive determination on the reported mechanical properties of bone cement for technological cutability and future estimation of minimal technological conditions for PMMA disintegration. Variables that influence the mechanical properties, such as handling characteristics, strain rate, loading modes, additives, porosity, blood inclusion, in vivo environment, temperature, etc. have to be also investigated. Future research areas important for full characterization of physical properties of PMMA are also suggested.

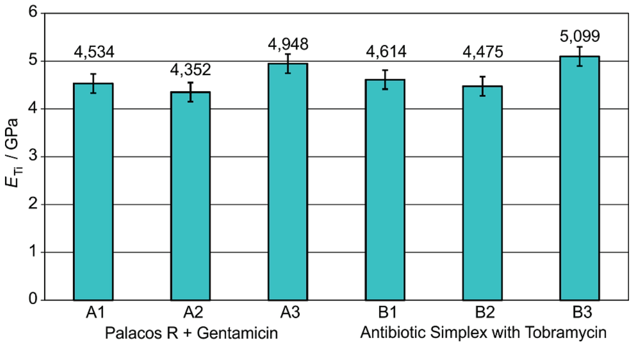

Figure 4 Young modulus of elasticity of bone cement

Effective surgical process depends on technology. Due to many benefits of water jet it is possible to use kinetic energy of waterjet for destruction of bone cement – interface between femoral stem and trabecular bone in case of reimplantation of femoral stems (Fig. 5). There is an advantage of using water jets coming from the fact that the jet is able to remove selectively the material with lower modulus of elasticity (titanium endoprosthesis exhibits modulus of elasticity E_{Ti} = 200 GPa, bone cement (PMMA) E_{bc} = 4,5 ÷ 4,8 GPa (Fig. 4), and trabecular bone tissue E_{bone} = 14,8 GPa [39]).

Considering low values of mechanical characteristics of bone cement the water jet flow shall cold-create a crack between a trabecular part of bone structure and the stem of the femoral component without mechanical damage or deformation to surrounding tissue during process of releasing of the stem of the component. This hypothesis was partially experimentally verified by disintegration of the bone cement sample with continuous water jet (Fig. 1 and Fig. 6a) and pulsating water jet (Fig. 2 and Fig. 6b).

Nine cuts were performed by continuous water jet using nozzle orifice d = 0,1 mm at pressure levels p = 40, 80, 120 MPa (Fig. 6). Visible traces were observed only at pressure of 80 and 120 MPa. Cracks are clearly visible at left part of the figure. Cuts are sharp and thin (Fig. 6a).

Apparently continuous water jet is not suitable for required destruction of bone cement, due to high pressure. The following Fig. 8 shows traces created by pulsating water jet using flat orifice Hammelmann d = 0,8 mm and spray angle 10°. Traces were created (from left to right) with pressure p = 16, 20, 12 MPa at standoff distance z = 4 mm. Last trace was created at pressure level p = 8 MPa and standoff distance z = 2 mm. Traverse speed in both cases was v = 1 mm/min which simulates the traverse speed of surgeon.

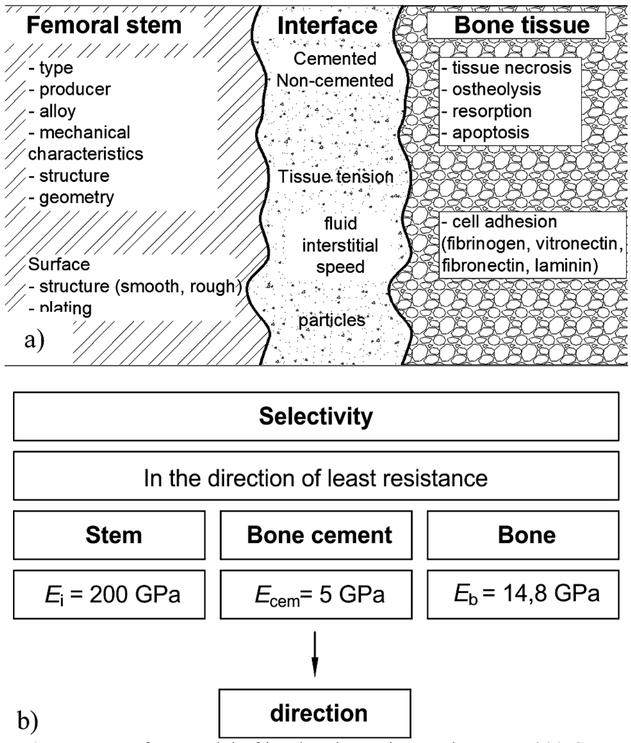

Figure 5 Interface model of implant bone tissue where E_i = 200 GPa, E_{cem}= 4,5 ÷ 4,8 GPa, E_{Bone} = 14,8 GPa (a), selectivity principle (b)

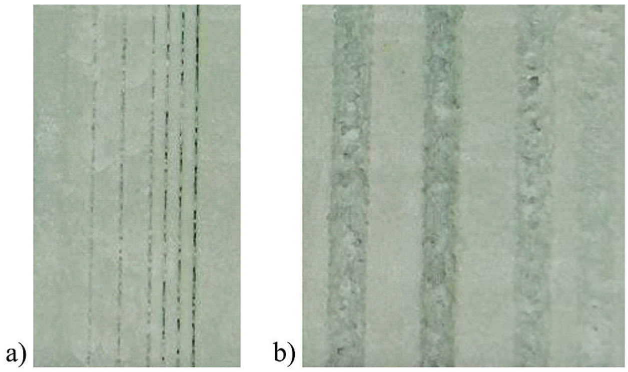

Figure 6 Detailed view on cutting traces a) continuous water jet, b) pulsating water jet (flat orifice)

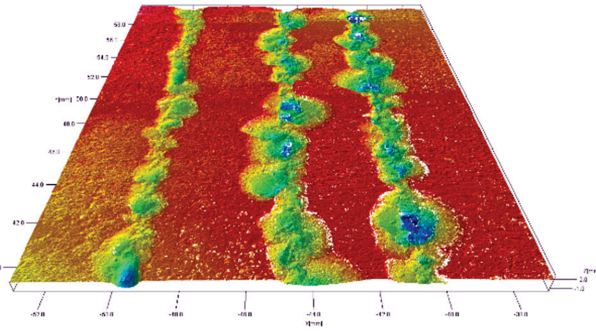

Figure 7 3D Profile record of Palacos R+G® surface disintegrated by continuous water jet d = 0,1mm

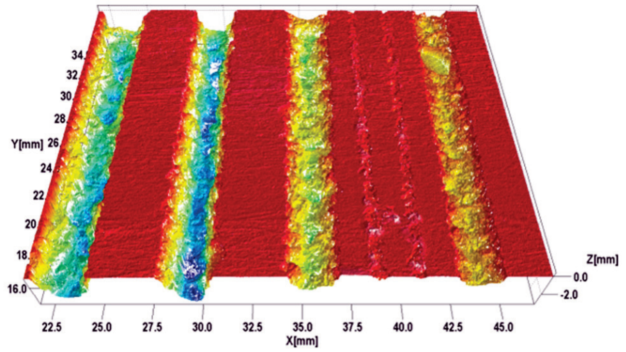

Figure 8 Palacos R+G® surface 3D profile obtained by MicroProf FRT – Traces created by pulsating water jet with flat orifice (Hammelmann) d = 0,8 mm – 10°

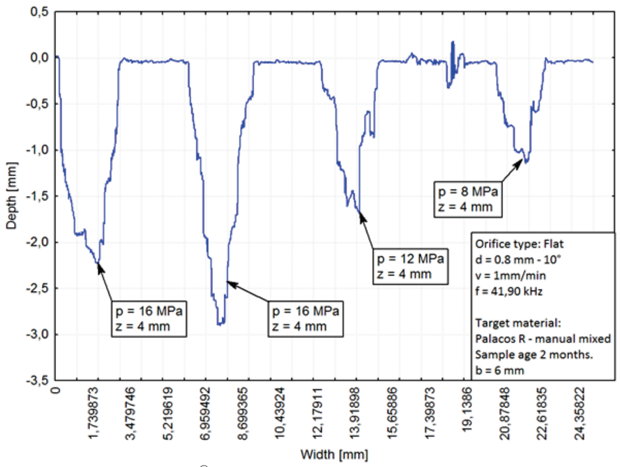

Figure 9 Palacos R+G® surface 2D depth profile obtained by MicroProf FRT – Traces created by pulsating water jet with flat orifice (Hammelmann) d= 0,8 mm – 10°

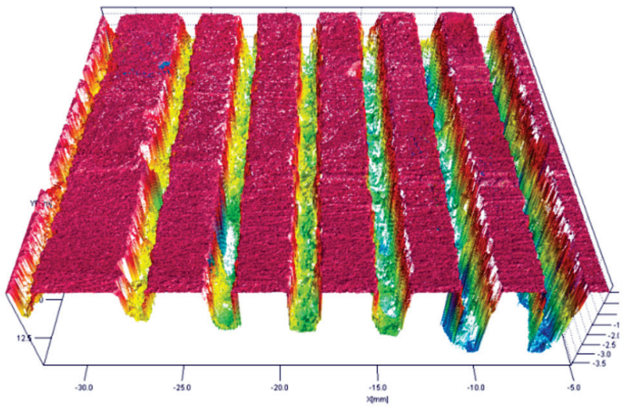

Figure 10 Palacos R+G® surface 3D profile obtained by MicroProf FRT – Traces created by pulsating water jet with circular orifice MVT d = 0,7 mm

When one compares traces created by continuous water jet and traces created by pulsating water jet, the traces created by pulsating water jet are much deeper. Depth achieved during bone cement disintegration with flat orifice d = 0,8 mm – 10° is shown in Fig. 9. Width of entry part of traces is approximately b = 2 mm. It is apparent that depth h (mm) decreases with the pressure decrease from h = 3 to 1 mm. Higher depths were achieved during disintegration of bone cement with circular orifice, as can be seen in Figs. 10 and 11.

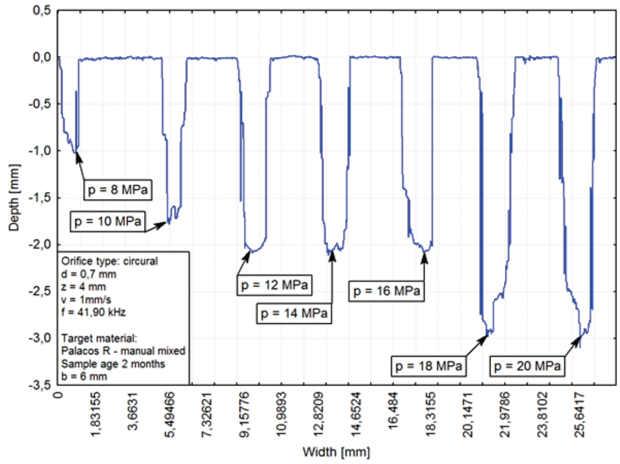

Figure 11 Palacos R+G® surface 2D depth profile obtained by MicroProf FRT – Traces created by pulsating water jet with circular orifice MVT d = 0,7 mm

Results from performed experiments show (Figs. 9 and 11), that the pulsating water jet is a suitable technology for bone cement removal due to the lowest pressures necessary for disintegration of bone cement. Further research will be aimed at the evaluation of disintegration of different kinds of bone cements commercially used in orthopaedic practise.

5 Conclusion and future direction of research

New technologies are still being introduced even in orthopaedic practice with a promise of better care of patients, though often with limited pieces of information. Therefore hospitals, medical establishments, and surgeons face a need to evaluate relative advantages of new technologies to be able to consider possible benefits for patients. The aim is to decrease costs and potential undesirable clinical impacts connected with their use. This scientific research work is based on the possibility to apply the water jet cutting technology. It comprises outcomes of exploration and possibilities of utilization of the water jet cutting technology and pulsating water jet for the purpose of responsible and profitable introduction of the technology in orthopaedic practice. Innovation of the exerted surgical procedures with utilization of the water jet in medicine is a vision to the near future with solid foundation in the fierce competitive market environment. Surgical operations using the water jet represent a potential instrument to enhance both surgical operations in favour of patient's life quality improvement and eventually general social and economic impact. In spite of considerable advance in the application of the water jet technology we are aware of the problems related to its application in clinical practice and thus we do believe that by the contribution a possible discussion focused on the field in question shall be initiated.

Acknowledgement

Experiments were carried out under the support of projects science and research VEGA 1/0972/11, VEGA 2/0075/13, Institute of clean technologies for mining and utilization of raw materials for energy use, reg. no. CZ.1.05/2.1.00/03.0082 supported by the Research and

Development for Innovations Operational Programme financed by the Structural Funds of the European Union and the state budget of the Czech Republic, and with support for the long term conceptual development of the research institution RVO:68145535.

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