ISSN 1330-3651 (Print), ISSN 1848-6339 (Online)
UDC/UDK 621.96.044.4:617.3

WATER JET TECHNOLOGY USING IN ORTHOPAEDIC SURGERY

Sergej Hloch, Ján Kľoc, Pavol Hreha, Dagmar Magurová, Dražan Kozak, Lucia Knapčíková

Subject review
The paper deals with potential uses of water jet technology and its modification for cutting of bone tissue and bio-materials. It summarises the present state of the art, defines problems from the technological and surgical point of view in order to increase the quality of treated clients. The paper represents an overview and the first step towards using water jet technique in orthopaedic surgery, during dissintegration of interface between bone and femoral stem.

Keywords: *bone total hip replacement, orthopaedic, water jet*

Uporaba tehnologije mlaza vode u ortopedskoj kirurgiji

Pregledni članak
Rad se bavi mogućnošću uporabe tehnologije vodenog mlaza i njegovom preinakom za rezanje koštanog tkiva i bio-materijala. Sažima sadašnje stanje znanja, definira probleme s tehnološke i kirurške točke gledišta, kako bi se povećala kvaliteta liječenih klijenata. Članak predstavlja pregled i prvi korak ka uporabi tehnike vodenog mlaza u ortopediji, tijekom rastavljanja međuspoja između kosti i bedrenog stabla.

Ključne riječi: *ortopedski, potpuna izmjena kosti kuka, vodeni mlaz*

1 Introduction

Material machining is a subject in continuous quality enhancement requiring systematic implementation of new technologies meeting highly demanding criteria given by flexible market environment and specific requirements related to the environment [1]. Nowadays even surgeons are being confronted with the need to bring the existing technologies into line with specific biomaterial properties and new biocompatible materials including titanium alloy, bone cements utilized in production of total replacements of hip joints [2, 3, 4, 5]. Water jet represents one out of the small amount of tools capable to satisfy rigid requirements even in the field of orthopaedic surgery [6, 7]. Bio-materials machining is one of the chief aspects of orthopaedic surgery. Oscillating saws, chisels still remain to be standard instruments inevitable for bone cutting and socket generation for endoprostheses [8, 9, 10, 11]. Negative side effects are distinctive heat and deformation impacts [21]. It is the application of the water jet that offers eventuality of eliminating the negative mentioned features [12] of technological process. The purpose of the study is also a more detailed examination and overall understanding of the application of the water jet cutting technology being in question with the application in orthopaedics and thus to contribute to its development in order to enhance both the quality of surgical operation [3, 4, 13] and nursing service for patients/clients (p/c) [14].

2 Related status

Latest knowledge of fundamental research [23, 24, 25] and up-to-date technology has established conditions [26, 27] and high potentials in the area of conventional orthopaedic surgical operations as for instance corrections of uneven length and deformations of limbs, osteosynthesis, but particularly in the possibilities of replacements of worn-out degenerative joints either on the developing, inflammatory, traumatogenic, metabolic grounds or in the postoperative states [6, 33]. Replacement of worn-out joints offers new treatment possibilities [18, 19, 20, 21]. Number of patients suffering from degenerative joint diseases (osteoarthritis) has been continually increasing and due to seriousness, therapeutic complications and frequent patient/client individualization the disease represents significant medical, economic and social issue [6, 22].

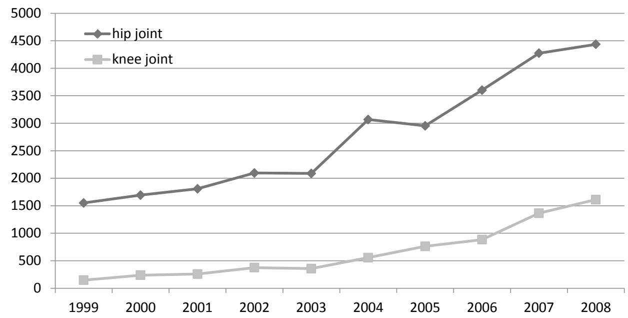

Figure1 Development of endoprosthetics (primarily) [22]

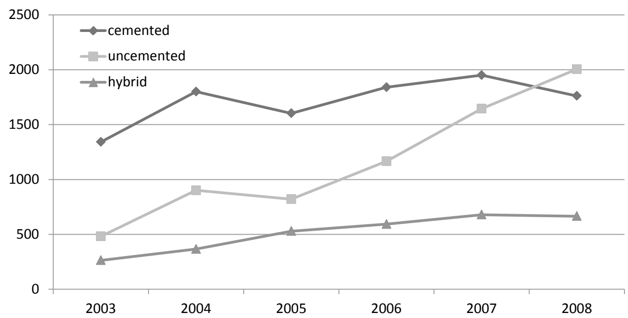

Figure 2 Development of methods of the hip joint fixation [22]

Progress being achieved in orthopaedics, specifically in the sphere of reconstructive surgery, allows partial even full return of a p/c to normal life. Damaged joint replacement by the total endoprosthesis represents the most remarkable advance in the history of bone surgery [6, 22, 32, 33]. For the patient the successful re(implantation) of destroyed joint means improvement of mobility, pain relief and returning back to accomplish every day activities. Many patients at working age come back to work after successful surgery of the hip joint.

Implantation achievement of the total hip joint replacement and long-term longevity of endoprosthesis depend on a lot of factors involving correct indication, patient preparation, properly performed surgical operation, surgeon's skills, technical device, operating theatre conditions and postoperative care in which rehabilitation plays an important role. Number of the hip joint total endoprostheses in the world and Slovak Republic increases yearly (Figs. 1 and 2) [22].

The presented development chart of number of alloplastic surgical operations of the hip and knee joints in the territory of the Slovak Republic draws on two sources: until 2003 it was statistics of the chief expert in orthpedics of Ministry of Health of the Slovak Republic and since 2003 it has been the Slovak Arthroplasty Register (SAR) [22]. Gradually, application of the cementless total hip joint replacements increases [6, 22].

3 Procedure analysis

Technical innovations in the sphere of total replacement development include multifactor impact on diverse joint aspects [2 ÷ 7], [28]. New contemporary techniques of osteotomy procedures allow precise cut final grinding and thus optimal prosthesis placing in the bearing axis. The result of this highly exact procedure is a more precise endoprosthesis fitting, fixation improvement and longevity [6]. Prior to each surgery related to the total endoprosthesis of the hip joint a preoperative planning is to be carried out allowing determining the size of the endoprosthesis components, their position following the anchoring in order to retain the centre of rotation of the total replacement (Fig. 3).

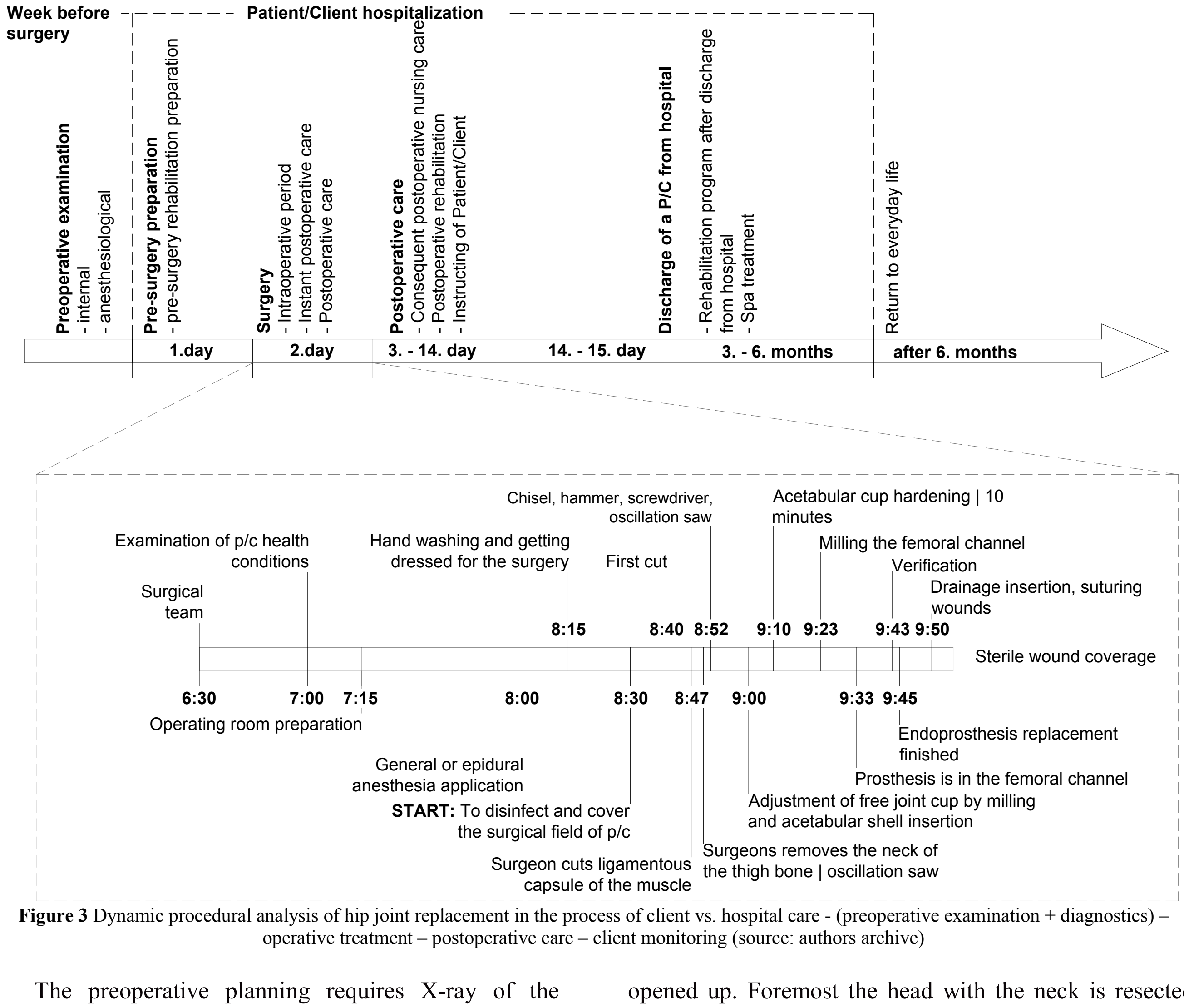

Figure 3 Dynamic procedural analysis of hip joint replacement in the process of client vs. hospital care - (preoperative examination + diagnostics) – operative treatment – postoperative care – client monitoring (source: authors archive)

The preoperative planning requires X-ray of the pelvis in the AP projection and the images of both hip joints in the axial projection. The planning of the size and position of the components is carried out using the templates. The surgery is possible to be performed using different operative approaches, according to the surgery type, and surgeon's usages. As per operative approach the operative technique and surgery procedure are different.

In standard anterolateral approach following the preparation of the soft structure the hip joint is being opened up. Foremost the head with the neck is resected and then the joint cup of the acetabulum is proceeded to in order to be machined. The acetabulum is being machined by the use of special milling cutters in accordance with the cup being implanted. Into the prepared socket of the acetabulum either the cemented cup is anchored using bone cement or the cementless cup in case of which the polyethylene, metal or ceramic articulation liner is inserted into the anchoring part.

Consequently, the femoral channel is prepared in case of which under the osteotomy line the metaphyseal area is being extended by means of fenestrated chisel. The chisel orientation has to retain the planned anteversion of the femoral component. Using special milling cutters the marrow cavity is then milled with the milling cutters' size increasing in stages. Thereafter the cavity is prepared by rasps according to the implanted endoprosthesis type. A plastic head is inserted onto the last rasp size, displacement is performed, endoprosthesis stability is tested and the length of the limb is checked [2, 6].

In cemented endoprosthesis the cap made of polyethylene or spongious bone is inserted into the cavity below the tip of the femoral component and so is the drainage which drains haematoma out of distal pole of the marrow cavity allowing thus bone cement to be pressed into the marrow cavity [6, 29]. The centralizer of an adequate size is inserted into the opening of lower part of the stem. Following the drainage removal the stem is inserted into the femoral channel filled with bone cement in desired anteversion. When cement has grown mature the testing head, later changed into the definite one, is reinserted. Should the cementless stem be used it is placed into the prepared socket to provide fixed anchoring.

4 Problems overview

Thanks to respected researchers such Pude [3], Schmolke [4], Honl [8, 9], Kušnerova [30], Kloc [6] and Foldyna [31] and more [8-29] and their very valuable published contributions we are now able to define new problems dealing with the application of waterjet in orthopaedic surgery and problems to be solved in order to successful introduction of that technology to surgical applications. Present reasons for further rising level of knowledge are possible to be formulated into the spheres as follows (Fig. 8):

- insufficient respect of physical and mechanical parameters of biomaterial with absence of unified mathematical formulations;
- absence of broad analytical and theoretical basis for application of the technology in medical practice;
- insufficient respect of physical and mechanical or stress and deformation integrity of the system: technological factors – tool – material – surface quality;
- many disadvantages related to the use of such instruments, whereas a risk of shattering, cracking and various other complications related to reimplantation of total replacement increases [6].
- absence of broad analytical and theoretical basis for application of the technology in medical practice;
- general fragmentation of interpretations and results of different research workplaces and thus improper reciprocal correlation;
- low level of generalization of results acquired at different workplaces;
- noticeable absence of unified biomaterial classification as per capability of being cut by particular technique.

5 Possible solution

Water jet term includes several modifications of water jets being differentiated by the individual authors from various perspectives. Classification of water jets as per Momber [38] is presented in the following scheme (Fig. 4). Momber classifies water jets into three basic groups – low-pressure and high-pressure, continuous-discontinuous, pure or water jets containing additives.

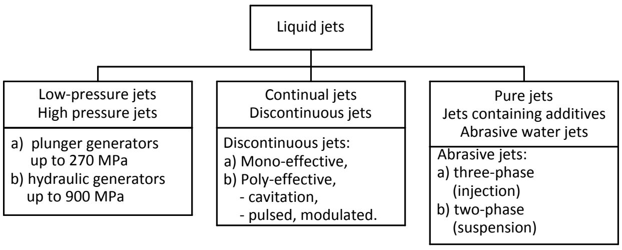

Figure 4 Scheme of water jet classification according to Momber [38]

Use of water jet as an instrument for orthopaedic purposes (Figs. 5, 6, 7), which may create any desired geometry with high accuracy, is proven in the experimental part and in several studies of foreign researchers [3, 4, 5, 8, 9, 13].

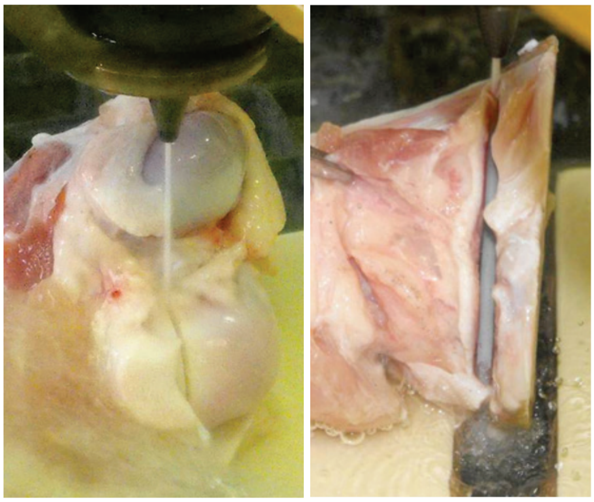

Figure 5 Athermic cutting of the pig bone by the water jet (ASCR Ostrava – Poruba)

Figure 6 Cutting of femoral stem with bone cement by abrasive water jet

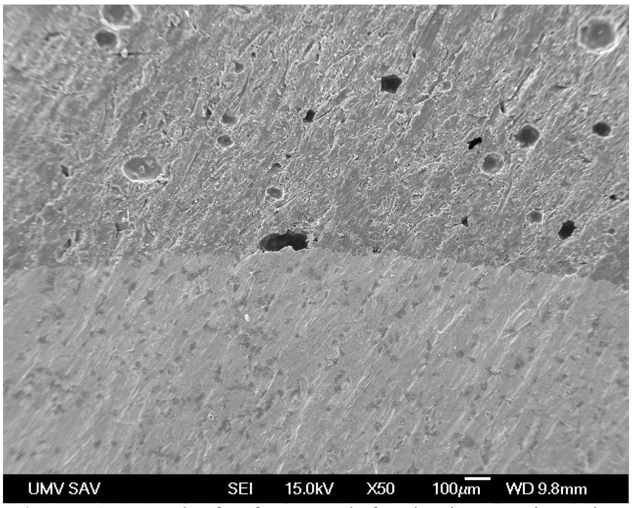

Figure 7 An example of surface created after abrasive water jet cutting with visible interface between femoral stem and bone cement

As garnet as the most available abrasive material cannot be used in medical applications due to insufficient biocompatibility and biodegradability, the main attention has recently been paid to searching for abrasive materials usable in medicine. Requirements related to an abrasive usable for medical purposes from the view of biocompatibility and biodegradability of particles and from the view of cutting performance were described in works. For medical applications, for instance, sorbitol, xylitol or sodium chloride (NaCl), may be used (Fig. 5). Apart from verified abrasives – sorbitol – table salt and sugar were also used in the experiments [7]. These abrasives were added to the water jet by specially adjusted dosimeter and tank. The highest performance of cutting was confirmed with NaCl. The biggest advantage of abrasive water jet cutting compared to standard methods of the bone cutting is a possibility to form athermic cuts of the bone tissues (Fig. 5).

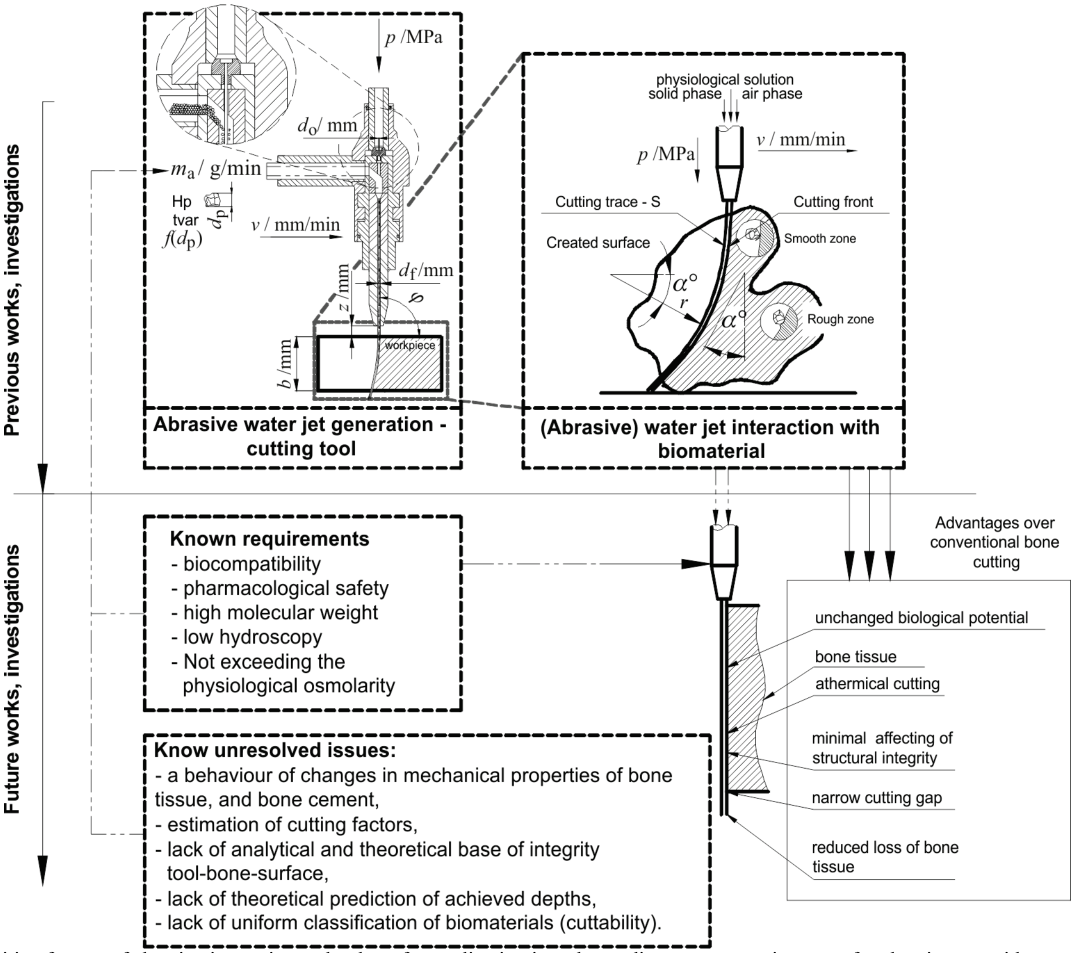

Figure 8 Positive feature of abrasive jet cutting technology for application in orthopaedic surgery, requirements for abrasive, new ideas to address problems identified

Low action of force in technological integrity: machine – tool – biological material indicates the use of modern manipulation systems and orthopaedic robots (Fig. 9). In this ex-vivo experimental study it was proven that the values of pressure have to be over 100 MPa and a new technical solution is required, which could provide for fluent feeding of a biocompatible abrasive to avoid a risk of potential embolism [3, 4, 7, 13]. Therefore it is necessary to work with higher pressures in the preparation of bone tissues and thus increase the amount of transformed power.

Considering benefits (Fig. 8) of selective cold removal by the water jet, pure water jet is used for tissue cutting. At the same time this study deals with a possibility of utilization of pure water jet and abrasive water jet as tools during reimplantation of total replacements. In regard to the removal selectivity it is possible to use the water jet also with low pressures to break up the interface formed by bone cement the physical and mechanical characteristics of which are diametrically different from those of the bone tissue or titanium endoprosthesis [8, 9, 29]. Disintegration of the surface of bone tissues and other biomaterials by water jet represents an issue interfering in several branches of clinical practice [2 ÷ 26]. Standard use of continual water jet involves surface disintegration, cutting of various kinds of materials, and removal of surface layers in case of surface cleaning. It is possible to significantly increase efficiency of impact of continual fluid jet by its modulation. Generation of high-frequency pressure pulsations [11, 35, 36, 37] 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 in case of reimplantations of cemented femoral stems.

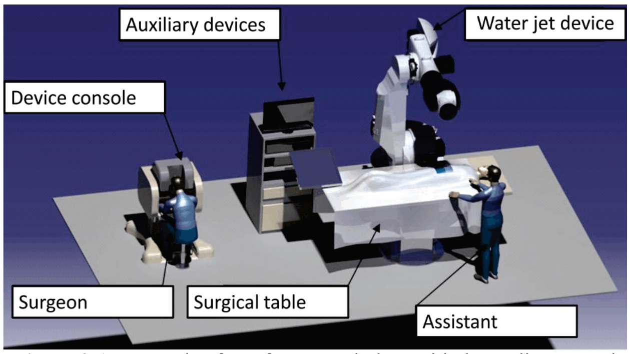

Figure 9 An example of pro-futuro workplace with the on-line control of surgical resection of the hip joint or reimplantation of total replacements of hip and knee joints by the abrasive water jet technology (source: Martina Blichova)

The reason is represented by the fact that due to the pressure pulsations the water jet flows out from the orifice as continual jet of water, but due to pulsation it has a variable axial component of velocity. In a certain distance from the orifice, this originally continual water jet is disintegrated to individual bursts of water and the jet behaves like the pulsating one. Disintegration ability of such pulsating jet increases significantly due to the fact that impact pressure generated by impingement of burst of water onto the material to be disintegrated is markedly higher than stagnation pressure generated by impingement of continual jet of equal parameters.

Kinetic energy E_k of the pulsating fluid jet may be used for destruction of bone cement in case of reimplantation of total replacements. Considering low values of mechanical characteristics of bone cement the jet flow shall cold-create a crack between a cortical 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.

6 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 upon possibility to apply the water jet cutting technology. It comprises outcomes of exploration and possibilities of utilization of the water jet technology for the purpose of responsible and profitable introduction of the technology in orthopaedic practice. Preferred advantages of the technology include absence of thermal impact upon material being machined. Potential benefits are:

- reduction of days in hospital,
- cost reduction,
- quality increasing,
- decrease of patient exposure to anaesthesia,
- replacement of a complex equipment for the mechanical extraction of the prosthesis,
- minimum X-ray exposure after prostheses reimplantation.

Yet the scope of further application is not limited. The sphere in which the technology is still being used on a small scale is medicine. The stage of the research is performed in cooperation with the Faculty of Health Care of University of Prešov, J. A. Reiman Teaching Hospital in Prešov, Institute of Geonics of Academy of Sciences of the Czech Republic in Ostrava, and the Faculty of Manufacturing Technologies in Prešov of Technical University in Košice.

Adequate medical care is to be based on the latest available procedures, techniques, and services with the purpose of quick, reliable and safe recovery of a p/c for their common life. In this case it is only a relict or habit to use the notion patient, which in the Latin language means enduring, suffering. The notion client has not been used at random but with a purpose. The purpose was not to draw attention to a detailed description of a p/c nursing care management after TEP but to centre on feasible innovative therapeutic techniques using the abrasive water jet in orthopaedics and orthopaedic nursing.

At the same time the desire was aimed at outlining the option of multidisciplinary connection in the field of medicine, nursing, and technical disciplines. The fundamental idea was a requirement to provide a p/c with the nursing care based on knowledge of the latest outcomes of a scientific research. A surgery related to TEP, utilizing abrasive water jet, represents a viable instrument for surgery enhancement. In perspective, it would be suitable, for instance, to work out standards and audit for complex nursing care of a p/c after TEP surgery with the application of a new surgical technology, monitoring of comfort of a surgical field, length of the surgery, keeping a p/c under anaesthesia, quality of after-surgical development with a p/c as well as the elimination of surgical complications due to earlier mobilisation. Last but not least the focus was directed towards benefits in the sense of increasing the quality of life of a p/c and thus related overall social and economic impact. However, quite a number of studies as well as activities should be performed aimed at the support and development of theoretical basis of medical and nursing research with further implementation in clinical practice. To acquire knowledge for more detailed description of the process it is inevitable to define indications and eventual contraindications in the application of the water jet in medicine.

Acknowledgement

Experiments were carried out under the project support science and research VEGA 1/0972/11 and by VEGA 2/0075/13.

7 References

[1] Sharma, V.; Chattopadhyaya, S.; Hloch, S. Multi response optimization of process parameters based on Taguchi-Fuzzy model for coal cutting by water jet technology // International Journal of Advanced Manufacturing Technology. 56, 9-12(2011), pp. 1019-1025.
[2] Hreha, P.; Hloch, S.; Magurová, D. et al. Water jet technology used in medicine. // Tehnički vjesnik - Technical Gazette. 17, 2(2010), pp. 237-240.
[3] Pude, F.; Schmolke, S.; Schwieger, K.; Honl, M.; Louis, H. Abrasive waterjets as a new tool for cutting of bone laboratory tests in the field of knee endoprostheses. // Proceedings of the 6th international conference on management of innovative technologies MIT2003, Ljubljana, 2003.
[4] Schmolke, S.; Pude, F.; Kirsch, L.; Honl, M.; Schwieger, K.; Krömer, S. Temperature measurements during abrasive water jet osteotomy. // Biomed Tech (Berl). 49, 1-2(2004), pp. 18-21.
[5] Kelmanovich, D. et al. Surgical Approaches to Total Hip Arthroplasty. // Journal of the Southern Orthopaedic Association, 12, 2(2003), pp. 90–94.
[6] Kľoc, J. Solutions disorders hip replacements, leading to reoperation. PhD Thesis, Technical University of Košice, 2009, p. 117.
[7] Hloch, S.; Valíček, J.; Kozak, D. Preliminary results of experimental cutting of porcine bones by abrasive waterjet // Tehnicki vjesnik-Technical Gazette, 18, 3(2011), pp. 467-470.
[8] Honl, M.; Rentzsch, R.; Lampe, F.; Müller, V.; Dierk, O.; Hille, E.; Louis, H.; Morlock, M. Water jet cutting for bones and bone cement-parameter study of possibilities and limits of a new method. // Biomed Tech Berlin. 45, (2000), pp. 222-227.
[9] Honl, M.; Rentzsch, R.; Müller, G.; Brandt, C.; Bluhm, A.; Hille, E.; Louis, H.; Morlock, M. The use of water-jetting technology in prostheses revision surgery-first results of parameter studies on bone and bone cement. // J Biomed Mater Res. 53, (2000), pp. 781-790.
[10] Ark, T. W.; Neal, J. G.; Thacker, J. G.; Edlich, R. F. Influence of irrigation solutions on oscillating bone saw blade performance. // J Biomed Mater Res vol. 43, (1998), pp. 108-112.
[11] Krause, W. R.; Bradbury, D. W.; Kelly, J. E.; Lunceford, E. M. Temperature elevations in orthopedic cutting operations. //J. Biomech. 15, (1982), pp. 267-275.
[12] Toksvig-Larsen, S.; Ryd, L.; Lindstrand, A. On the problem of heat generation in bone cutting: studies on the effects of liquid cooling. // J. Bone Joint Surg. 73B, (1991), pp. 13-15;
[13] Kuhlmann, C.; Pude, F.; Bishup, C. et al. Evaluation of potential risks of abrasive water jet osteotomy in-vivo. // Biomedizinische Technik. 50, (2005), pp. 337-342.
[14] Smith, T. et al. Bed exercises following total hip replacement: a randomised controlled trial. Physiotherapy, vol. 94, 4(2008), pp. 286-291.
[15] Salgado, A. J.; Coutinho, O. P.; Reis, L. R. Bone tissue Engineering: State of teh Art and Future Trends. // Macromol. Biosci. 4, (2004), pp. 743-765.
[16] Birth, M.; Kleemann, M.; Hildebrand, P. et al. Intraoperative online navigation of dissection of the hepatical tissue - a new dimension in liver surgery? // CARS 2004 - Computer Assisted Radiology and Surgery. DOI: 10.1016/j.ics.2004.03.335.
[17] Penchev, R. D.; Losanoff, J. E.; Kjossev, K. T. Reconstructive renal surgery using a water jet. // Journal of Urology. 162, (1999), pp. 772-774.
[18] Lustmann, J.; Ulmansky, M.; Fuxbrunner, A.; Lewis, A. 193 nm excimer laser ablation of bone // Lasers Surg Med. 11, (1991), pp. 51-57.
[19] Biyikli, S.; Modest, M. F. Energy requirements for osteotomy of femora and tibiae with a moving CW CO2 laser // Lasers Surg Med. 7, (1987), pp. 512-519.
[20] Wächter, R.; Stoll, P. Increase of temperature during osteotomy. // J. Oral Maxillofac. Surg. 20, (1991), pp. 245-249.
[21] Udiljak, T.; Ciglar, D.; Skoric, S. Investigation into bone drilling and thermal bone necrosis. Advances in Production Engineering and Management, 2, 3(2007), pp. 103-112.
[22] Nečas, L. et al. Slovak arthroplastic register – analysis. 2003-2008. 2009, pp. 325.
[23] Wallace, R. J.; Whitters, C. J.; McGeough, J. A.; Muir, A. Experimental evaluation of laser cutting of bone. // Journal of Materials Processing Technology. 149, (2004), pp. 557-560.
[24] O'Daly, B.; Morris, E.; Gavin, G.; O'Byrne, J.; McGuinness, G. High-power low-frequency ultrasound: A review of tissue dissection and ablation in medicine and surgery // Journal of Materials Processing Technology. 200, 1-3(2008), pp. 38-58.
[25] Cadavid, R.; Jean, B.; Wuestenberg, D. On the selection of the nozzle geometry and other parameters for cutting corneal flaps with waterjets. // Biomedizinische Technik. 54, (2009), pp. 134-141.
[26] Patel, K. J.; Chen, F. L. Increasing cut surface quality with various cutting orifice head oscillations for abrasive aqua jet machining, I // Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 217, (2003), pp. 1037-1040.
[27] Hakan, T. Fuzzy AHP based decision support system for technology selection in abrasive water jet cutting processes. // Tehnicki vjesnik-Technical Gazette, 18, 2(2011), pp. 187-191.
[28] Reynolds, L. A.; Tansey, E. M. Early Development of Total Hip Replacement. The Trhustee of the Welcome Trust, London, (2007), p. 200
[29] Postawa, P.; Szarek, A. Analysis of changes in bone cement damping factor and its effect on bone load. // Journal of Achievements in Materials and Manufacturing Engineering, 23, 1(2007), pp. 35-38.
[30] Augustin, G. et al. Temperature changes during cortical bone drilling with a newly designed step drill and an internally cooled drill. // International orthopaedics. 36, 7(2012), pp. 1449-1456.
[31] Augustin, G. et al. Cortical bone drilling and thermal osteonecrosis // Clinical biomechanics. 24, 4(2012), pp. 313-325.
[32] Rokosz, K.; Hryniewicz, T.; Raaen, S. Characterization of Passive Film Formed on AISI 316L Stainless Steel after Magnetoelectropolishing in a Broad Range of Polarization Parameters, Steel Research International, 2012, DOI: 10.1002/srin.201200046
[33] Hryniewicz, T.; Konarski, P.; Rokosz, K.; Rokicki, R. SIMS analysis of hydrogen content in near surface layers of AISI 316L SS after electrolytic polishing under different conditions, Surface & Coatings Technology, Vol. 205, (2011), 4228–4236, DOI: 10.1016/j.surfcoat.2011.03.024.
[34] Ruggiero, A. et al. Approximate closed-form solution of the synovial fluid film force in the human ankle joint with non-Newtonian lubricant. // Tribology International, 57, 1(2013), pp. 156-161.
[35] Kušnerová, M. et al. Derivation and measurement of the velocity parameters of hydrodynamics oscillating system. //

Strojarstvo: Journal for theory and application in mechanical engineering. 50, 6(2008), pp. 375-379.
[36] Foldyna, J. et al. Erosion of metals by pulsating water jet. // Tehnicki vjesnik-Technical Gazette, 19, 2(2012), pp. 381-386 .
[37] Riha, Z.; Foldyna, J. Ultrasonic pulsations of pressure in a water jet cutting tool // Tehnicki vjesnik-Technical Gazette, 19, 3(2012), pp. 487-491.
[38] Momber, W., A., Kovacevic, R. Principles of Abrasive Water Jet Machining. Springer-Verlag Berlin Heidelber, 1998, New York.

Authors' addresses

Sergej Hloch
Faculty of Manufacturing Technologies
of Technical Universtity of Košice with a seat in Prešov
Bayerova 1 080 01 Prešov
Slovak Republic
hloch.sergej@gmail.com

Ján Kľoc
J. A. Reiman Faculty Hospital with Policlinics in Prešov
Department of Orthopaedics
Slovak Republic
kloc@fnsppresov.sk

Pavol Hreha
Faculty of Manufacturing Technologies
of Technical Universtity of Košice with a seat in Prešov
Bayerova 1 080 01 Prešov
Slovak Republic

Dagmar Magurová
Faculty of Health Care of PU in Prešov
Partizánska 1, 080 01 Prešov, Slovakia
Slovak Republic
magurod0@unipo.sk

Dražan Kozak
J. J. Strossmayer University of Osijek
Mechanical Enginnering Faculty in Slavonski Brod
Trg Ivane Brlić-Mažuranić 2
HR-35000 Slavonski Brod, Croatia
dkozak@sfsb.hr

Lucia Knapčíková
Faculty of Manufacturing Technologies
of Technical Universtity of Košice with a seat in Prešov
Bayerova 1 080 01 Prešov
Slovak Republic
knapcikova.lucia@gmail.com