Photobiomodulation Therapy in the Proliferation and Differentiation of Human Umbilical Cord Mesenchymal Stem Cells: An In Vitro Study

Jéssica Meirinhos Miranda1,2*, José Alcides Almeida de Arruda3, Lara Marques Magalhães Moreno1,2, Wyndly Daniel Cardoso Gaiaõ4, Sílvio Vinícius Barbosa do Nascimento1,2, Eduardo Vinícius de Souza Silva1,2, Márcia Bezerra da Silva1, Cláudio Gabriel Rodrigues4, Diana Santana de Albuquerque5, Rodivan Braz2, Antonio Luiz Barbosa Pinheiro6, Marleny Elizabeth Marquez de Martinez Gerbi1,2

1Laser Center, School of Dentistry, Universidade de Pernambuco, Camaragibe, PE, Brazil
2Department of Restorative Dentistry and Endodontics, School of Dentistry, Universidade de Pernambuco, Camaragibe, PE, Brazil
3Department of Oral Surgery and Pathology, School of Dentistry, Universidade Federal de Minas Gerais, Belo Horizonte, MG, Brazil
4Department of Biophysics and Radiobiology, Universidade Federal de Pernambuco, Recife, PE, Brazil
5Center of Biophotonics, School of Dentistry, Universidade Federal da Bahia, Salvador, BA, Brazil

Abstract

Introduction: Since photobiomodulation therapy (PBMT) favors in vitro mesenchymal stem cell (MSC) preconditioning before MSC transplantation, increasing the proliferation of these cells without molecular injuries by conserving their characteristics, in the present in vitro study we analyzed the effect of PBMT on the proliferation and osteogenic differentiation of human umbilical cord mesenchymal stem cells (hUCMSCs).

Methods: Irradiation with an InGaAIP Laser (660 nm, 10 mW, 2.5 J/cm², 0.08 cm² spot size, and 10 s) was carried out. The cells were divided into four groups: CONTROL [cells grown in Dulbecco’s Modified Eagle Medium (DMEM)], OSTEO (cells grown in an osteogenic medium); PBMT (cells grown in DMEM+PBMT), and OSTEO+PBMT (cells grown in an osteogenic medium plus PBMT). The cell proliferation curve was obtained over periods of 24, 48 and 72 hours using the 3-(4,5-dimethyl-2-thiazolyl)-2,5-diphenyl-2H-tetrazolium bromide (MTT) assay. Osteogenic differentiation was analyzed by the formation of calcium nodules over periods of 7, 14 and 21 days. Morphometric analysis was performed to quantify the total area of nodular calcification.

Results: The highest cell proliferation and cell differentiation occurred in the OSTEO+PBMT group, followed by the PBMT, OSTEO and CONTROL groups respectively, at the observed times (P < 0.05).

Conclusion: PBMT enhanced the osteogenic proliferation and the differentiation of hUCMSCs during the periods tested, without causing damage to the cells and preserving their specific characteristics, a fact that may represent an innovative pretreatment in the application of stem cells.

Keywords: Photobiomodulation; Lasers, Stem cells; Cell differentiation.

Introduction

Due to their potential application to tissue regeneration and formation, mesenchymal stem cells (MSCs) have been studied in different areas in order to replace conventional treatments.1 MSCs are undifferentiated and have the potential for application to cell therapy because of their characteristics of self-renewal, proliferation, and differentiation into various types of specialized cells.2 One of the findings that makes the use of MSCs interesting in the clinical setting, is their ability to migrate to the damaged tissue or toward inflammatory sites after intravenous administration.3

The human umbilical cord contains MSCs with a high potential for cell proliferation that can be isolated in a relatively easy, painless, and noninvasive manner. In addition, these cells pose a low risk of infection and show multipotency and more rapid self-renewal properties compared to bone marrow MSCs.4,5 To be used for cell therapy, MSCs must be expanded in vitro. Thus, growth factors can be used in culture media as osteogenic inductors
in order to promote appropriate cell expansion.\textsuperscript{6} Growth factors stimulate and guide stem cells so that they will proliferate and differentiate into osteoblasts, adipocytes or chondroblasts under standard \textit{in vitro} differentiating conditions.\textsuperscript{7} Over the last few years, photobiomodulation therapy (PBMT) has been indicated as an effective process in regenerative medicine and dentistry due to its cellular stimuli and biomodulator effects \textit{in vitro} and \textit{in vivo}.\textsuperscript{8,12} PBMT enhances MSC proliferation and differentiation by energy absorption by intracellular chromophores, producing adenosine triphosphate (ATP) and increasing DNA activity as well as RNA and protein synthesis.\textsuperscript{12}

Since PBMT favors \textit{in vitro} MSC preconditioning before MSC transplantation, increasing the proliferation of these cells without molecular injuries by conserving their characteristics,\textsuperscript{13,14} we conducted an \textit{in vitro} study in order to determine the effect of PBMT on the proliferation and osteogenic differentiation of human umbilical cord mesenchymal stem cells (hUCMSCs). Also considering the few studies of this type available in the literature, our objective was to determine whether the irradiation parameters employed contributed in a positive manner to cell proliferation and differentiation.

**Materials and Methods**

**Cell Culture**

Patients’ anonymity was guaranteed according to the Helsinki Declaration. Human umbilical cords were obtained from cesarean deliveries carried out at a private hospital in Recife, Brazil. Wharton’s jelly cells of umbilical cord were isolated and placed in culture flasks containing Dulbecco’s Modified Eagle’s Medium (DMEM, Gibco, CA, USA) supplemented with 15% fetal bovine serum (FBS, Gibco, CA, USA), 20% Ham F-12 (Gibco, CA, USA), penicillin (10 000 unit/mL) (Gibco, CA, USA), and streptomycin (Sigma Aldrich, SP, Brazil), 1 mM β-glycerophosphate (Sigma Aldrich, SP, Brazil), and 10 nM dexamethasone (Sigma Aldrich, SP, Brazil). The cell culture medium was changed every 72 hours during the 21 days of the experiment.

After 24 hours of plating, PBMT and OSTEO+PBMT cells were irradiated with the InGaAIP laser (660 nm) (MMOptics\textsuperscript{8}, Equipamentos Ltd., São Carlos, SP, Brazil) as follows: continuous mode, 10 mW, 2.5 J/cm\textsuperscript{2} spot size and 10 seconds. Before irradiation, the plates were covered with black cardboard with only one orifice perforated according to the diameter of the wells due to the scattering characteristics of irradiation. The experiments were carried out in a standardized manner using a claw-shaped adapter attached to the tip of the equipment positioned 6 cm below the center of the well of the culture plates.\textsuperscript{15} In view of the scattering characteristics of laser radiation, the wells were intercalated so that no energy accumulation would occur.

**MTT Assay**

A solution containing 0.5 mg/mL 3-(4,5-dimethyl-2-thiazolyl)-2,5-diphenyl-2H-tetrazolium bromide (MTT, Sigma Aldrich) was added to the wells and the plates protected from light were incubated at 37°C for 4 hours. DMEM combined with MTT was then removed from the wells and dimethyl sulfoxide (DMSO, Sigma, SP, Brazil) was added in order to solubilize the crystals formed. Absorbance at 590 nm was read with a spectrophotometer (Flx 800, Fluorescence Microplate Reader software, version 2.06.10, BIOTEK, Winooski, VT, USA) and the cells were analyzed at intervals of 24, 48 and 72 hours in order to construct the cell proliferation curve.

**Alizarin Red Stain**

A solution containing 0.5 mg/mL 3-(4,5-dimethyl-2-thiazolyl)-2,5-diphenyl-2H-tetrazolium bromide (MTT, Sigma Aldrich) was added to the wells and the plates protected from light were incubated at 37°C for 4 hours. DMEM combined with MTT was then removed from the wells and dimethyl sulfoxide (DMSO, Sigma, SP, Brazil) was added in order to solubilize the crystals formed. Absorbance at 590 nm was read with a spectrophotometer (Flx 800, Fluorescence Microplate Reader software, version 2.06.10, BIOTEK, Winooski, VT, USA) and the cells were analyzed at intervals of 24, 48 and 72 hours in order to construct the cell proliferation curve.

The analysis was carried out 7, 14 and 21 days after the beginning of incubation. After culture in inductor and control media with and without irradiation, each well was washed three times with PBS for the complete removal of the media. The cells were fixed in 300 µL 10% paraformaldehyde for 20 minutes at room temperature and then treated with 300 µL Alizarin Red (Sigma) for 15 minutes for the detection of nodular calcium formation. The wells were then abundantly washed with deionized water in order to remove excess dye and the wells of each experimental group were photographed with a camera coupled to an inverted light microscope at 40× magnification (Leica DM1000, Leica Microsystems Wetzlar GmbH, Germany). The images obtained were analyzed with LAS Interactive Measurement software.
PBMT in Human Umbilical Cord Mesenchymal Stem Cells

Data Analysis
The histomorphometry data were analyzed by one-way ANOVA complemented with the Tukey test, with the level of significance set at 5% (P<0.05), using Origin (Pro) software, version 8 (Origin Lab Corp., Northampton, MA, USA).

Results
Immunophenotyping on hUCMSCs
hUCMSCs were found to be positive for adhesion molecules (CD44, 51.3%), marker protein of integrin (CD29, 54.4%) and extracellular matrix proteins (CD90, 84.1%), whereas they were found to be negative for hematopoietic markers (CD34, 91.3% and CD45, 90.9%) and the endothelial marker (CD31, 92.3%).

MTT Assay
The cell proliferation curves based on optical density values obtained from absorbance reading with a spectrophotometer after the MTT assay according to time of induction (24, 48 and 72 hours) for each group are shown in Figure 1. We observed that the highest concentration of cell proliferation was achieved in the irradiated groups OSTEO+PBMT, followed by PBMT. No statistically significant difference (P>0.05) was observed between the groups 24 hours after induction. After 48 and 72 hours of induction, there was no statistically significant difference (P>0.05) between the CONTROL and OSTEO groups, although there was a significant difference (P<0.05) between the CONTROL group and the PBMT and OSTEO+PBMT groups, as well as between all experimental groups.

Morphological and Morphometric Features
Morphological analysis of the culture plate wells agreed with the morphometric analysis. Osteogenic activity was observed according to the formation of calcium nodules. Seven days after induction there was an increase in osteogenic activity in the OSTEO+PBMT group, followed by the PBMT, OSTEO and CONTROL groups (Figure 2). The increase in activity was maintained among the groups 14 and 21 days after induction, with the following groups showing the greatest osteogenic activity in increasing order: CONTROL, OSTEO, PBMT followed by OSTEO+PBMT.

Discussion
Stem cell therapy is a promising treatment for the induction of bone regeneration. In addition, several studies have confirmed that PBMT increases the viability, migration, proliferation and induction of differentiation of stem cells from different tissues, favoring the preconditioning of these cells before their transplantation. In the present study, we investigated the effect of PBMT on the proliferation and osteogenic differentiation of hUCMSCs and demonstrated a synergism of the association of PBMT with the osteogenic medium, increasing the proliferation and osteogenic differentiation of these cells.

It is known that the molecular mechanism promoted in cells by PBMT is associated with increased gene expression of anti-inflammatory cytokines, including interleukin (IL) 1-alpha and IL-6, as well as inhibition of IL-1β by human keratinocytes following laser irradiation. Thus, these cell responses are believed to occur through the synthesis of ATP, the increased potential of the mitochondrial membranes and the levels of cyclic adenosine monophosphate. In this regard, in order to use PBMT, it is important to establish the parameters of irradiation since different standards may produce different effects, especially regarding cell proliferation, inducing stimulatory or inhibitory responses. Indeed, when we compared the irradiation parameters used, we observed ample divergence between these variables, demonstrating the lack of protocol standardization and the consequent modification of the results.
Accordingly, we used a laser with a 660 nm wavelength that was able to induce positive biomodulatory effects.\textsuperscript{10,15} In line with this, Fekrazad et al\textsuperscript{7} reported promising results about MSC proliferation using a laser with a wavelength in the 600-700 nm range. In contrast, other studies\textsuperscript{28,29} applying a wavelength of 808 nm to one of their experimental groups did not obtain positive biomodulatory effects regarding MSC proliferation and viability, which is probably due to the high energy density (20 mW/cm\textsuperscript{2}) used. Indeed, it has been observed that low energy power and density values do not damage the cellular photoreceptors and consequently contribute to the biomodulatory effect of a laser.\textsuperscript{10,15,29-31}

Zaccara et al\textsuperscript{15} used dental pulp stem cells (DPSCs) irradiated with laser (0.5 and 1.0 J/cm\textsuperscript{2}) and de Andrade et al\textsuperscript{32} treated adipose tissue-derived mesenchymal stem cells (AD-MSC) with a 660 nm laser, with 40 mW power and 0.56, 1.96 and 5.04 J energy. Both authors reported a statistically significant difference between the irradiated and control groups after the MTT assay, demonstrating that PBMT promoted the proliferation of both DPSCs and AD-MSC. Our results agree with these previous reports since the hUCMSCs studied here showed increased cell viability and proliferation when associated with PBMT. It is worth mentioning that higher energies such as 5.04 J may be harmful to cell biostimulation.\textsuperscript{32}

In the current study, the optical density values obtained showed that cell proliferation was even higher for the 72 hours time point after the beginning of induction, followed by the 48 and 24 hours time points. These results agree with those reported by Yang et al,\textsuperscript{33} who observed the highest optical density in the group treated with LED light associated with the osteogenic medium on days five and seven. Although the cited study used LED light (with a central band of 620 nm) in contrast to the present study which used a 660 nm laser, these similar results may be explained by the fact that a laser emits coherent light and LED emits non-coherent light, but both sources have photobiological effects when used with similar irradiation parameters.\textsuperscript{34}

Interestingly, we observed that the groups treated with PBMT had a larger area of mineralized nodules, with an even higher osteogenic activity in the group in which this treatment was combined with the medium for osteogenic induction. In line with this, Wang et al\textsuperscript{17} used a laser at densities of 2 and 4 J/cm\textsuperscript{2} in combination with a medium of osteogenic differentiation and observed that this treatment significantly promoted the proliferation and osteogenesis of bone marrow MSCs on the 7th and 21st days after the beginning of induction. In addition, studies investigating the effects of PBMT on the neural differentiation of hUCMSCs\textsuperscript{35} have reported promising results demonstrating that a 635 nm laser increased cell proliferation and that an 808 nm laser combined with cerebrospinal fluid favored neural differentiation in MSCs, showing that the combination of PBMT with the biological inductor contributed to cell differentiation according to the medium to which MSCs were added.\textsuperscript{35}
Despite the difficulty in comparing the experimental results obtained here with PBMT to those obtained in previous studies due to the variation in the irradiation parameters and the different cell tissue used, the present results suggest that the combination of PBMT with hUCMScs can improve the in vitro expansion of these cells, increasing their proliferation and osteogenic differentiation in order to achieve an appropriate quantity of cells for future implantation for bone tissue regeneration.

Conclusion
In summary, the osteogenic proliferation and differentiation of hUCMScs after induction were higher in the cells submitted to the osteogenic medium associated with PBMT with the parameters employed in this study, a relevant fact that may represent an innovative pretreatment in the application of stem cells, increasing cell proliferation without causing cell damage, maintaining its specific characteristics. Further studies associating UCMSc with PBMT are needed in order to establish the parameters of laser therapy with future clinical applicability.

Ethical Considerations
The study was approved by the Ethics Committee of the University of Pernambuco (No. 49503715.0.0000.5208).

Conflict of Interests
The authors declare no conflict of interest.

References
1. de Sá Silva F, Almeida PN, Rettore JV, Maranduba CP, de Souza CM, de Souza GF, et al. Toward personalized cell therapies by using stem cells: seven relevant topics for safety and success in stem cell therapy. J Biomed Biotechnol. 2012;2012:758102. doi: 10.1155/2012/758102.
2. De Los Angeles A, Ferrari F, Xi R, Fujiwara Y, Benvenisty N, Deng H, et al. Hallmarks of pluripotency. Nature. 2015;525(7570):469-478. doi: 10.1038/nature15515.
3. Otus K, Kumakami-Sakano M, Fujiwara N, Kikuchi K, Keller L, Lesot H, et al. Stem cell sources for tooth regeneration: current status and future prospects. Front Physiol. 2014;5:36. doi: 10.3389/fphys.2014.00036.
4. Ding DC, Chang YH, Shyu WC, Lin SZ. Human umbilical cord mesenchymal stem cells: a new era for stem cell therapy. Cell Transplant. 2015;24(3):339-347. doi: 10.3727/096368915X686841.
5. Hassan G, Bahjat M, Kasem I, Soukkarieh C, Aljamali M. Platelet lysate induces chondrogenic differentiation of umbilical cord-derived mesenchymal stem cells. Cell Biol Mol Biol Lett. 2018;23:11. doi: 10.1186/s11658-018-0080-6.
6. Naderi H, Matin MM, Bahrami AR. Review paper: critical issues in tissue engineering: biomaterials, cell sources, angiogenesis, and drug delivery systems. J Biomater Appl. 2011;26(4):383-417. doi:10.1177/0885328211408946.
7. Fekrazad R, Asefi S, Allahdadi M, Kalhori KAM. Effect of photobiomodulation on mesenchymal stem cells. Photomed Laser Surg. 2016;34(11):533-542. doi: 10.1089/pho.2015.4029.
8. Çakmak AS, Çakmak S, Vatansever HS, Gümüşderelioğlu M. Photostimulation of osteogenic differentiation on silk scaffolds by plasma arc light source. Lasers Med Sci. 2018;33(4):785-794. doi: 10.1007/s10103-017-2414-4.
9. Soares DM, Ginani F, Henriques ÁG, Barboza CA. Effects of laser therapy on the proliferation of human periodontal ligament stem cells. Lasers Med Sci. 2015;30(3):1171-1174. doi: 10.1007/s10103-013-1436-9.
10. Yin K, Zhu R, Wang S, Zhao RC. Low-level laser effect on proliferation, migration, and antiapoptosis of mesenchymal stem cells. Stem Cells Dev. 2017;26(10):762-775. doi: 10.1089/scd.2016.0332.
11. Engel KW, Khan I, Arany PR. Cell lineage responses to photobiomodulation therapy. J Biophotonics. 2016;9(11-12):1148-1156. doi: 10.1002/jbio.201600025.
12. de Freitas LF, Hamblin MR. Proposed mechanisms of photobiomodulation or low-level light therapy. IEEE J Sel Top Quantum Electron. 2016;22(3):7000417. doi: 10.1109/JSTQE.2016.2561201.
13. Mvula B, Abrahamse H. Differentiation potential of adipose-derived stem cells when cocultured with smooth muscle cells, and the role of low-intensity laser irradiation. Photomed Laser Surg. 2016;34(11):509-515. doi: 10.1089/pho.2015.3978.
14. Li Y, He L, Pan S, Zhang L, Zhang W, Yi H, et al. Three-dimensional simulated microgravity culture improves the proliferation and odontogenic differentiation of dental pulp stem cell in PLGA scaffolds implanted in mice. Mol Med Rep. 2017;15(2):873-878. doi: 10.3892/mmr.2016.6042.
15. Zaccara IM, Ginani F, Mota-Filho HG, Henriques ÁC, Barboza CA. Effect of low-level laser irradiation on proliferation and viability of human dental pulp stem cells. *J Biomed Biotechnol*. 2012;2012:758102. doi: 10.1155/2012/758102.
17. Wang L, Wu F, Liu C, Song Y, Guo J, Yang Y, et al. Low-level laser irradiation modulates the proliferation and the osteogenic differentiation of bone marrow mesenchymal stem cells under healthy and inflammatory condition. *Lasers Med Sci.* 2019;34(1):169-178. doi: 10.1007/s10103-018-2673-8.

18. Park IS, Mondal A, Chung PS, Ahn JC. Vascular regeneration effect of adipose-derived stem cells with light-emitting diode phototherapy in ischemic tissue. *Lasers Med Sci.* 2015;30(2):533-541. doi: 10.1007/s10103-014-1699-9.

19. Blatt A, Elbaz-Greener GA, Tuby H, Maltz L, Siman-Tov Y, Ben-Aharon G, et al. Low-level laser therapy to the bone marrow reduces scarring and improves heart function post-acute myocardial infarction in the pig. *Photomed Laser Surg.* 2016;34(11):516-524. doi: 10.1089/pho.2015.3988.

20. Bayat M, Virdi A, Rezaei F, Chien S. Comparison of the in vitro effects of low-level laser therapy and low-intensity pulsed ultrasound therapy on bony cells and stem cells. *Prog Biophys Mol Biol.* 2018;133:36-48. doi: 10.1016/j.pbiomolbio.2017.11.001.

21. Peplow PV, Chung TY, Ryan B, Baxter GD. Laser photobiomodulation of gene expression and release of growth factors and cytokines from cells in culture: a review of human and animal studies. *Photomed Laser Surg.* 2011;29(5):285-304. doi: 10.1089/pho.2010.2846.

22. Zajdel A, Kalucka M, Kokoszka-Mikolaj E, Wilczok A. Osteogenic differentiation of human mesenchymal stem cells from adipose tissue and Wharton's jelly of the umbilical cord. *Acta Biochim Pol.* 2017;64(2):365-369. doi: 10.18388/abp.2016_1488.

23. Hamblin MR. Mechanisms and Mitochondrial Redox Signaling in Photobiomodulation. *Photochem Photobiol.* 2018;94(2):199-212. doi: 10.1111/php.12864.

24. Pinheiro ALB, Gerbi MEM. Photoengineering of bone repair processes. *Photomed Laser Surg.* 2006;24(2):169-178. doi: 10.1089/pho.2006.24.169.

25. Ozkan S, Isildar B, Oncul M, Baslar Z, Kaleli S, Koyturuk M. Ultrastructural analysis of human umbilical cord derived MSCs at undifferentiated stage and during osteogenic and adipogenic differentiation. *Ultrastruct Pathol.* 2018;42(3):199-210. doi: 10.1080/01913123.2018.1453905.

26. Huang YY, Nagata K, Tedford CE, McCarthy T, Hamblin MR. Low-level laser therapy (LLLT) reduces oxidative stress in primary cortical neurons in vitro. *J Biophotonics.* 2013;6(10):829-838. doi: 10.1002/jbio.201200157.

27. Anders JJ, Lanzafame RJ, Arany PR. Low-level light/ laser therapy versus photobiomodulation therapy. *Photomed Laser Surg.* 2015;33(4):183-184. doi: 10.1089/ pho.2015.9848.

28. Bouvet-Gerbettaz S, Merigo E, Rocca JP, Carle GF, Rochet N. Effects of low-level laser therapy on proliferation and differentiation of murine bone marrow cells into osteoblasts and osteoclasts. *Lasers Surg Med.* 2009;41(4):291-297. doi: 10.1002/lsm.20759.

29. Chen H, Wang H, Li Y, Liu W, Wang C, Chen Z. Biological effects of low-level laser irradiation on umbilical cord mesenchymal stem cells. *Aip Adv.* 2016;6(4):045018. doi: 10.1063/1.4948442.

30. Karu T. Photobiology of low-power laser effects. *Health Phys.* 1989;56(5):691-704. doi: 10.1097/00004032-198905000-00015.

31. Min KH, Byun JH, Heo CY, Kim EH, Choi HY, Pak CS. Effect of low-level laser therapy on human adipose-derived stem cells: In vitro and in vivo studies. *Aesthetic Plast Surg.* 2015;39(5):778-782. doi: 10.1007/s00266-015-0524-6.

32. de Andrade ALM, Luna GF, Brassolatti P, Leite MN, Parisi JR, de Oliveira Leal AM, Frade MAC, et al. Photobiomodulation effect on the proliferation of adipose tissue mesenchymal stem cells. *Lasers Med Sci.* 2019;34(4):677-683. doi: 10.1007/s10103-018-2642-2.

33. Yang D, Yi W, Wang E, Wang M. Effects of light-emitting diode irradiation on the osteogenesis of human umbilical cord mesenchymal stem cells in vitro. *Sci Rep.* 2016;6:37370. doi: 10.1038/srep37370.

34. Shimizu N, Mayahara K, Kiyosaki T, Yamaguchi A, Ozawa Y, Abiko Y. Low-intensity laser irradiation stimulates bone nodule formation via insulin-like growth factor-1 expression in rat calvarial cells. *Lasers Surg Med.* 2007;39(6):551-559. doi: 10.1002/lsm.20521.

35. Chen H, Wu H, Yin H, Wang J, Dong H, Chen Q, et al. Effect of photobiomodulation on neural differentiation of human umbilical cord mesenchymal stem cells. *Lasers Med Sci.* 2019;34(4):667-675. doi: 10.1007/s10103-018-2638-y.