Ultrasound-mediated Microbubble Destruction Promotes Bone Marrow Mesenchymal Stem Cell Transplantation for Myocardial Infarction Therapy

Fuchao Yu, Jinyu Li, Zhuo Xu, Zhouchou Lu, Xiaohui Zhang, Dan Li and Jiayi Tong*

Institute of Cardiology, Southeast University, Nanjing, Jiangsu Province, China

*Correspondence author: Jiayi Tong, Institute of Cardiology, Southeast University, Nanjing 210009, Jiangsu Province, China, Tel: +86-25-83262415; E-mail: 13701464321@163.com

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Abstract

The study was designed to investigate whether ultrasound-mediated microbubble destruction can enhance the transplantation of bone marrow mesenchymal stem cells (BMSCs) for myocardial infarction therapy. Twenty myocardial infarction pigs were assigned into the ultrasound microbubble destruction group (n=12), Sonovue were infused into coronary artery with ultrasonic radiation, then BMSCs were injected into infarction region and the cell control group (n=8, only subjected to BMSCs treatment). The increase of left ventricular ejection fraction was larger in the ultrasound microbubble destruction group (P<0.01), and more Prussian blue-positive cells and higher density of heart muscle capillary in the peripheral infarct regions were found (P<0.01). Prussian blue-positive cells were differentiated into new vascular endothelial cells in two cases, among which the gaps were widened in the microbubble destruction group. Our study first time testifies in pig models that ultrasound-mediated microbubble destruction promotes BMSC transplantation for myocardial infarction therapy.

Keywords: Ultrasound; Microbubble; Bone marrow; Mesenchymal stem cells; Transplantation; Myocardial infarction

Introduction

Myocardial infarction is caused by the loss of myocardial cells and decreased cardiac systolic and diastolic functions, and inevitably leads to heart failure. It has been reported that intramyocardial stem cell transplantation can notably increase the perfusion of blood in ischemic myocardium and improve heart functions [1,2]. The extent of improvement is linearly correlated with the number of colonized stem cells in the heart [3]. Among the various transplantation methods, intramyocardial injection can have the highest transplantation efficiency, on the order of 10%. Intra-coronary artery transplantation achieves the second highest efficiency, usually 1% to 2%, although 10% has also been reported [4]. Since these results are not satisfying, it is of great importance to look for novel and effective approaches to increase the efficiency of stem cell transplantation.

Ultrasound is a type of wave motion that has several biological effects, such as mechanical and sonic cavitation effects. Radiation pressure is generated when ultrasound is transmitted across different tissues, and it can induce the marginal accumulation of blood cells by pushing them to the vascular wall. Ultrasound microbubble contrast agents in liquid can serve as the cavitation nuclei. In response to ultrasound, the microbubbles undergo asymmetric contraction and expansion and are prone to rupture, which markedly widens the gaps between vascular endothelial cells and elevates the membrane permeability. This effect may also give rise to transient and reversible pores in the membrane, increase the permeability of the biological barriers around the tissues where the microbubbles rupture, and ultimately elevate the efficiency of stem cell transplantation.

The present study investigated the influence of the ultrasound-mediated microbubble destruction on the stem cell transplantation therapy against myocardial infarction and provided objective data for clinical therapeutic strategies of stem cell transplantation.

Materials and methods

Experimental design

Randomized controlled animal studies were performed in the Medical College of the Southeast University from October 2006 to May 2008.

Materials

In total, 20 pigs, aged 2 months and weighing 29 ± 1 kg, were provided by the experimental animal center of the Clinical Medical College of the Southeast University. Pigs were randomly assigned into the ultrasound microbubble destruction group (n=12) and the cell control group (n=8). All animals were treated according to the Guidelines for Virtuous Treatment of Experimental Animals that was released by the Science and Technology Ministry in 2006. Reagents and instruments were listed in table 1.

<table>
<thead>
<tr>
<th>Reagents and equipment’s</th>
<th>Resources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fetal bovine serum</td>
<td>Hangzhou Sijiqing Biological Engineering Materials</td>
</tr>
<tr>
<td>DMEM (Low glucose)</td>
<td>Gibco</td>
</tr>
<tr>
<td>Ficol, trypsin</td>
<td>Sigma</td>
</tr>
<tr>
<td>Trypan blue</td>
<td>Beyotime Institute of Biotechnology</td>
</tr>
<tr>
<td>Prussian blue Kit</td>
<td>Shanghai Chunzhu Biotechnology</td>
</tr>
<tr>
<td>Superparamagnetic iron oxide</td>
<td>Research Center for Nanotechnology, Southeast University</td>
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obtained is sufficient. A total of 30 ml bone marrow fluid was transferred into a 50 ml sterile centrifuge tube. MSCs and HBSCs were collected each time, confirming the amount of bone marrow fluid separated by density centrifugation on Ficoll. The supernatant was diluted with low-glucose DMEM medium containing 10% FCS. Then the MSCs were seeded at a density of 2-3×10^2 cells/cm^2. The culture solution was changed in 25 ml culture flasks, the culture fluid was regularly refreshed every 2-3 days. Passage cultured with super-paramagnetic iron oxide particles that were coated with arginine for 24 h. Cells were then trypsinized, precipitated by centrifugation and re-suspended in fresh medium. Cell survival rates were measured using trypan blue staining [6,7].

**Methods and observation indexes**

**In vitro culture of bone marrow mesenchymal stem cells (BMSCs)**

The animals were subjected to intramuscular induction of anaesthesia using ketamine in a dose of 10-15 mg/kg behind the pig ear. Once anaesthesia is induced, a 0.01 g/kg pentobarbital sodium was intravenously injected to maintain anaesthesia.

Anterior superior iliac spine was chosen as puncture site after conventional sterilization. After puncture, 50 ml syringe containing 1000 Units heparin was used to collect bone marrow, and 5 ml was collected each time, confirming the amount of bone marrow fluid obtained is sufficient. A total of 30 ml bone marrow fluid was transferred into a 50 ml sterile centrifuge tube. MSCs and HBSCs were separated by density centrifugation on Ficoll. The supernatant was diluted with low-glucose DMEM medium containing 10% FCS. Then the MSCs were seeded at a density of 2-3×10^4 in 25 ml culture flasks, and then incubated at 37 in 5% CO2. The culture solution was changed 48h after incubation, removed the non-adherent cells. After that, the culture fluid was regularly refreshed every 2-3 days. Passage cultured when MSCs reached 80%-90% confluence. The MSCs were purified after multiple passages. Generally, the stem cells for transplantation were harvested after passage 3.

**Establishment of the acute myocardial infarction model**

The animals were subjected to induction of anaesthesia as described above. Once anaesthesia is induced, the needle was inserted at the maximum pulse point of right lower limb femoral artery. Guide wire and catheter were inserted through sheathing canal in femoral artery. The site of left anterior descending branch was identified using radiography. Then guide wire was placed at left anterior descending branch. OTW Foley’s tubes with proper size were chosen by using coronary arteriography, and were placed at the distal one-third site of the left anterior descending branch. Refill through the tubes with the same stress following ischemic preconditioning. The elevation of ST-segment in anterior precordial leads indicated that heart muscle ischemia has been caused by ischemic preconditioning. Filling through the tubes was maintained for 60 min to establish the model of acute anterior myocardial infarction. Subsequently, the models were transferred to animal laboratory [5].

**Labeling of BMSCs with super-paramagnetic iron oxide**

Thirteen days after model establishment, BMSCs were incubated with super-paramagnetic iron oxide particles that were coated with arginine for 24 h. Cells were then trypsinized, precipitated by centrifugation and re-suspended in fresh medium. Cell survival rates were measured using trypan blue staining [6,7].

**Transplantation of BMSCs**

Fourteen days after model establishment, animals were subjected to MSCs implantation through coronary artery. The procedures are as follows: The animals underwent coronary arteriography. When TIMI grade III flow was observed, guide wire was inserted through OTW Foley’s tubes into the middle segment of the left anterior descending branch. OTW Foley’s tubes were dilated afterwards. Totally, 2.4 ml SonoVue was infused into the pigs via perfusion catheter in ultrasound microbubble destruction group. Using X-ray observation, ultrasonic detector was positioned at the distal one-third site of the left anterior descending branch (myocardial infarction). The necrosis area was treated with ultrasonic radiation at a dosage of 1 MHz and 2 W/cm^2 for 90 seconds. Subsequently, 5×10^6 isolated MSCs labelled by superparamagnetic iron oxide were injected into the pigs. In contrast, the pigs in the cell control group were only subjected to the injection of BMSCs [8].

**Histological characterization and ultrastructure observation**

Samples from the cell control group were collected at 0 h and 6 weeks after transplantation, whereas samples from the ultrasound microbubble group were collected at 0 h, 24 h and 6 weeks after transplantation. Samples from 4 animals were collected at each time point. Normal regions, infarct border regions and infarct regions in the heart were selected for examination. Some of the collected tissues were fixed by formaldehyde and used for preparation of 3 μm thick paraffin sections. Sections were stained with hematoxylin-eosin or Prussian blue. The sections from the 6 week samples were also used for immunohistochemical staining of desmin and capillary counting. Other tissues were fixed with glutaraldehyde and subjected to scanning electron microscopy to examine the ultrastructure of vascular endothelial cells.

**Examination of heart functions by 64-spiral computerized tomography (CT)**

All animals were examined by 64-spiral CT (scanning slice thickness 0.6 mm) at 1 day before and 6 weeks after transplantation. End-diastolic volume, end-systolic volume and left ventricular ejection fraction (LVEF) were obtained by image processing approaches such as volume rendering, multilayer reconstruction and maximum intensity projection.

**Statistical analysis**

Data were analysed using the statistic software SPSS (version 11.5) and were expressed as x ± s. Comparisons between groups were carried out by a single factor analysis of variance. Significant differences are defined as P<0.05.

**Results**

**Quantitative analysis of experimental animals**

The model of myocardial infarction was successfully established in each of the 20 experimental pigs. No animals were lost during the experiment.

**Labelling of BMSCs with super-paramagnetic iron oxide and the cell viability test**

Before transplantation, BMSCs labelled by super-paramagnetic iron oxide were mounted on slides and stained with Prussian blue. Blue particles in the cytoplasm and red nuclei were observed under a microscope. The labelling rate was nearly 100%. No blue particles
could be found in the unlabelled BMSCs. In addition, the survival rate of the labelled and unlabelled BMSCs was about 98% before transplantation, as demonstrated by trypan blue staining.

**Changes of heart functions**

The LVEFs of the animals in both groups were significantly decreased 1 day before transplantation. No significant difference was observed between the groups (P>0.05), which suggested that myocardial infarction had a similar influence on heart functions of the animals in both groups. Six weeks after transplantation, the LVEFs in both groups were notably elevated compared with the fractions before transplantation, and the increment in the ultrasound microbubble destruction group was significantly higher than that in the cell control group (P<0.01) (Table 2).

<table>
<thead>
<tr>
<th>Time</th>
<th>Ultrasound microbubble group</th>
<th>Cell control group</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>LEDV (mL)</td>
<td>LSV (mL)</td>
</tr>
<tr>
<td>1 day pretransplantation</td>
<td>59.75 ± 0.95</td>
<td>32.25 ± 0.96</td>
</tr>
<tr>
<td>6 wk aftertransplantation</td>
<td>61.75 ± 0.96</td>
<td>27.75 ± 1.71</td>
</tr>
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</table>

Table 2: Comparison of cardiac function in both groups before and after transplantation LEDV: Left Ventricular End Diastolic Volume; LSV: Left Ventricular End Systolic Volume; LVEF: Left Ventricular Ejection Fraction; *P<0.01 vs. the cell control group

**Histological characterization of myocardium**

**Hematoxylin-eosin staining**

Infarcted cardiac fibres were dissolved in the infarct regions. Myocardial structure could not be seen and was substituted by infiltrated erythrocytes and neonatal fibroblasts, lymphocytes and capillaries. Dispersed fresh acute infarct regions that had not been repaired were also observed, and they were demarcated by the lack of myocardial structure and cell nuclei. In contrast, it was found that the myocardial structure in the peripheral infarct regions was intact. In these locations, fibroblasts, lymphocyte infiltration and neonatal capillaries were seen.

**Prussian blue staining**

Prussian blue-positive cells could be seen in the samples of both groups, even at 6 weeks after transplantation; however, more positive cells were found in the ultrasound microbubble destruction group (P<0.01). Prussian blue-positive cells were predominantly distributed in the peripheral infarct regions (Figure 1a). In two cases, Prussian blue-positive cells were differentiated into new vascular endothelial cells (Figure 1b).

**Immunohistochemical staining of desmin**

Six weeks after transplantation, desmin-positive cells could be seen in samples from both groups (Figure 2).

**The density of capillaries**

The density of capillaries in the peripheral infarct regions was significantly higher in the ultrasound microbubble destruction group than in the cell control group (P<0.05) (Figure 3).

**Ultrastructure changes of vascular endothelial cells**

Observation of ultrastructure demonstrated that the integrity of vascular endothelial cells with diameters of about 6 µm was disrupted. Karyopyknosis and chromatin margination on the nuclear membrane were also observed. No thrombosis was seen in the vessel lumen (Figure 4). Notably, there was no obvious difference in these ultrastructure changes between the two groups. Moreover, at 0 h after transplantation, a widened gap between two endothelial cells was seen in a blood vessel with a diameter of 11.5 µm in the ultrasound.
microbubble destruction group, but not in the cell control group (Figure 5).

![Figure 3: Compare of capillary density between control group and microbubble group](image)

**Figure 3:** Compare of capillary density between control group and microbubble group

Our data showed that ultrasound-mediated microbubble destruction increased the efficiency of intramyocardial BMSC transplantation, which was demonstrated by greater numbers of Prussian blue-positive cells in the ultrasound microbubble destruction group than in the cell control group. This result is consistent with the finding of Takanobu et al., who reported that low-frequency ultrasound associated with microbubble destruction increased the efficiency of BMSC transplantation into ischemic skeletal muscle [11]. Ghanem et al. recently found that targeted endothelial adhesion and myocardial engraftment after intravascular delivery of MSCs can be enhanced with hf-UMS [12]. These effects may arise from the biological responses to ultrasound-mediated microbubble destruction. These responses include the radiation pressure generated by ultrasound transmission through different tissues, the shear stress generated by microbubble rupture, and the cavitation effect generated by ultrasound-mediated microbubble destruction. Radiation pressure can promote the local accumulation of blood cells by pushing them to the vascular wall, whereas cavitation can induce the contraction of endothelial cells, the widening of gaps between endothelial cells and the subsequent destruction of microvessels [13,14]. Moreover, shear stress can help the transplanted cells in the blood vessel to penetrate the vessel wall and enter tissues. In addition, slight damage-induced inflammatory responses that result from ultrasound-mediated microbubble destruction can also promote the production of inflammatory factors (e.g. interleukin-1) and induce the intramyocardial migration of mesenchymal stem cells. Expression of adhesion molecules is up-regulated in damaged endothelial cells, which allow the circular mesenchymal stem cells to stick to the damaged vascular endothelium via adhesion molecules and avoid blood scouring. All these biological responses facilitate the entrance of transplanted BMSCs into damaged myocardium and increase the efficiency of BMSC transplantation. Indeed, our results demonstrated
that ultrasound-mediated microbubble destruction notably elevated transplantation efficiency. The integrity of vascular endothelial cells with diameters of about 6 µm was disrupted. Chromatin margination on the nuclear membrane and widened gaps between endothelial cells were also observed.

Ultrasound-mediated microbubble destruction promoted myocardial neovascularization. Immunohistochemical staining showed that the myocardial capillary density was significantly higher in the ultrasound microbubble destruction group than in the control group. Aseptic inflammation induced by microvascular fracture during ultrasound-mediated microbubble destruction can promote myocardial neovascularization, which may increase blood flow in normal and ischemic myocardium [15-18]. It has been reported that transplanted BMSCs can be secrete vascular endothelial growth factors and basic fibroblast growth factors under certain conditions [19,20]. Moreover, the BMSCs transplanted into myocardium can differentiate into not only myocardial-like cells but also into vascular endothelial-like cells. All these biological effects can induce neovascularization in ischemic myocardium.

BMSC transplantation with ultrasound-targeted microbubble destruction can increase the colonization of stem cells in the infarct regions and the infarct border regions make more stem cells differentiate into myocardial cells, synergistically facilitate angiogenesis, and improve blood supply in both the infarct regions and the peripheral infarct regions. This transplantation strategy may improve cardiac blood perfusion, especially in hibernating and stunned myocardium, and lead to the recovery of systolic function in hibernating myocardium. It also provides the appropriate microenvironment for the survival of transplanted stem cells and their differentiation into myocardial cells. The strategy can also limit ventricular dilatation, especially in the ventricular scar region, inhibit cardiac remodelling, ameliorate cardiac systolic and diastolic functions and ultimately improve cardiac functions impaired by myocardial infarction. In conclusion, the present work suggested a new strategy for the transplantation of intramyocardial BMSCs. This approach may have widespread application in the treatment of myocardial infarction.

Especially, we used spiral CT rather than ultrasonic radiation in the present study due to the fact that the statistical analysis by ultrasonic radiation was more likely to be affected by operator subjectivity compared with by spiral CT. In addition, ultrasonic radiation may potentially produce more errors when measuring the volume of irregular-shaped ventricles, which formed under the symptoms of myocardial infarction and ventricular aneurysm. Second, ultrasonic analysis was one of the affecting factors in our study, which might increase the potential interfering factors during cardiac function analysis. Spiral CT ensures accurate positioning. The device provides accurate data according to the left ventricular volume, quality and functional evaluation, and it is highly reproducible and less affected by operator subjectivity. Compared with MRI, spiral CT needs less scan time and has lower requirements of animal cooperation. The availability of better cardiac post-processing techniques is also a benefit. It has been reported that the LVEF is better correlated with spiral CT measurement than with MRI measurement [21,22]. Therefore we chose to use spiral CT rather than MRI in the present study.

The present study had several limitations. First, the number of experimental samples was relatively small. Whether the findings in our study could be applied into clinical practice still requires further intense investigations with large sample size. Surprisingly, recent studies proposed the promising prospect of applying ultrasound microbubbles into treatment of myocardial infarction through stem cell transplantation. Song et al suggested that using US-mediated MB destruction prior to BMSCs transplantation into the infarcted myocardium improves the effectiveness of cardiac cell therapy and cardiac function in rabbits [23]. Second, the respective functions of the ultrasound and microbubbles on the transplantation of BMSCs were not analysed in more detail. Third, the physical and molecular mechanisms by which ultrasound-mediated microbubble destruction improves cell homing ability remain unclear [24]. In addition, the exact mechanisms by which stem cells transplantation ameliorated cardiac systolic function and the roles of extracellular matrix during this process also warrant clarification. It is still unknown whether myocardial-like cells differentiated from transplanted BMSCs have systolic and neovascularization functions. Future investigations will focus on these issues.

Acknowledgments

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References


