Extracellular matrix from decellularized mesenchymal stem cells improves cardiac gene expressions and oxidative resistance in cardiac C-kit cells

Wai Hoe Ng a, Rajesh Ramasamy b, Yoke Keong Yong c, Siti Hawa Ngalim a, Vuanghao Lim a, Bakiah Shaharuddin a, Jun Jie Tan a, *

a Advanced Medical and Dental Institute, Universiti Sains Malaysia, Bertam, 13200 Kepala Batas, Penang, Malaysia
b Department of Pathology, Faculty of Medicine and Health Sciences, Universiti Putra Malaysia, Serdang, 43400 Selangor Darul Ehsan, Malaysia
c Department of Human Anatomy, Faculty of Medicine and Health Sciences, Universiti Putra Malaysia, Serdang, 43400 Selangor Darul Ehsan, Malaysia

1. Introduction

The discovery of resident cardiac cells (CCs) has caught the attention of clinicians as these cells could be a promising alternative treatment for treating myocardial infarcted patients. Cardiac c-kit cells (CCs) were first found present in adult rat heart [1], and subsequently being successfully isolated in human [2]. These cells exhibit stem cell characteristics and they are clonogenic, self-renewal and able to differentiate into cardiomyocytes, smooth
muscle and endothelial cells [1,3]. The ability of these CCs in regenerating hearts have been observed in both the rat [1,4] and mice [5,6] through the formation of new myocytes and vasculatures. In addition, they protect the pre-existing cardiomyocytes from apoptosis and increased the survival by modulating IGF-1/IGF-1R/Akt pathway in swine model [7,8]. They also play important roles in cardiomyogenesis in embryonic and neonatal heart development [9], the formation of new cardiomyocytes following myocardial infarction and responsible for cardiac cellular homeostasis in the heart [4,10].

CCs have been the light of hope for autologous stem cell therapy, which exclude the hurdles in immunogenic rejection following transplantation. Nonetheless, stem cell homing, survival and engraftment are important key factors for successful cell-based therapy. Low oxygen supplied and lack of blood flow in infarcted heart limit the survival of transplanted cells following transplantation [11,12], which lead to failure in stem cell treatment. Researchers have tried to overcome this problem by preconditioning transplanted cells with growth factors and genetic modifications of stem cell prior to transplantation in order to increase survival of cells. For example, by genetically engineered mesenchymal stem cells (MSCs) overexpressing CXCR4 in combination with SDF-1 improved survival and engraftment of MSCs in rodents' hearts [13]. However, most of the transplanted cells loss during the first few hours of transplantation and die within a short period [14]. Therefore, higher number of transplanted cells has been suggested to increase the probability of cell engraftment. Intracoronary infusion of 10 million CCs in pigs or equivalent to 40 million CCs in human are proven to be safe [15]. Even though high cell number could be transplanted to increase engraftment efficiency, these cells often underwent another programmed cell death called anoikis, which is induced by weak cell–matrix interaction [16]. Moreover, long term in vitro expansion of CCs in order to obtain sufficient cells for CC transplantation could lead to erosion and replicative senescence. Therefore, a new approach has to be investigated in order to solve these problems.

ECM regulates cell–matrix functions through interaction with ECM proteins and provides mechanical supports to the cells [17,18]. Natural scaffolds derived from organs is performed by perfusion-decellularisation and then recellularised with suitable stem cell candidate to build a new bioartificial heart [19]. The heart scaffold is decellularised using detergents to omit antigenic properties but preserving the architecture of the heart [19]. However, this technology is not feasible as it is limited by donor availability, scalability and long processing time [20]. Therefore, cell-specific ECM may be useful for cell therapy approaches as a source of biological scaffolds, which offers the advantage in maintaining the structure of their respective tissues and organs.

Cell sheet engineering technology has shown to improve the efficiency and efficacy of cell engraftment through cell–cell interactions [21]. The transplantation of cell sheet composed of rat or human CCs into the infarcted rat hearts were found to improve the CC survival, proliferation, migration and cardiomyocyte differentiation [21]. Lu et al. (2011) demonstrated that cell-derived ECM scaffolds from MSCs, normal human articular chondrocytes and normal human dermal fibroblast-derived ECM support cell adhesion and proliferation differently to their respective cells [22].

The cell-deposited ECM from umbilical cord MSCs enhances antioxidant properties and facilitates in vitro cell expansion of the same cell type, which is likely due to in vivo microenvironment mimicking from cell-specific ECM [23]. Implantation of heart tissue-derived decellularised matrix has shown improvement in left ventricular infarcted wall thickening and LVEF after MI in rats [24]. Transplantation of CCs in combination with heart-derived ECM also improved CC survival and engraftment, and preserved heart structure in rats [25]. Human fibroblast-derived ECM enhanced MSC proliferation [26]. Human MSC-derived ECM enhanced Schwann cell proliferation and promoted the secretion of neurotrophic factors for peripheral nerve repair [27].

MSCs were isolated from gelatinous Wharton Jelly from pregnant women [28] which exhibit the characteristics provided by the International Society of Cellular Therapy (ISCT), including the ability for plastic adherence, expressing CD105, CD73 and CD90, and able to differentiate to adipocytes, osteoblasts and chondroblasts [29]. As compared to bone marrow MSCs, WJMSCs have higher proliferation rate [30]. Therefore, in this study, we aim to employ MSCs derived from Wharton jelly for ECM generation. Wharton Jelly is commonly discarded after birth as biological waste, yet they are readily available and ethically acceptable sources for allogeneic primary MSCs. MSCs obtained from Wharton Jelly possesses high proliferation rates and higher stemness due to the early embryological origin. More importantly, the isolated MSCs are multipotent and exhibit stem cell characteristics. The effect of MSC-ECM on CCs were assessed by proliferation, oxidative stress assay and cardiomyocyte differentiation efficiency.

2. Materials and methods

2.1. Isolation and characterisation of cardiac c-kit cells from mice

The protocol for isolating cardiac c-kit cells (CCs) was adapted from Smits et al. (2009), with slight modification [31]. All procedures were performed according to guidelines approved by the Institutional Animal Care and Use Committee (IACUC) of Universiti Sains Malaysia [USM/Animal Ethics Approval/2014/(91) (547)]. Briefly, whole heart was extracted from 4 to 6 week old C57BL/6N mice immediately following carbon dioxide asphyxiation. Heart tissue was collected in ice-cold Dulbecco's Modified Eagle Medium: Nutrient Mixture F-12 (DMEM/F12), supplemented with 20% foetal bovine serum, and 1× Penicillin and Streptomycin (Gibco®; Thermo Fisher Scientific, Carlsbad, CA, USA). The collected heart was washed in cold-M buffer to remove residual blood by gently pressing with sterile forceps. Upon removal of non-heart tissues, the heart was minced into small pieces of about 1 mm³ and digested in 1 mg/ml Collagenase A (Roche Applied Science, Indianapolis, IN, USA) for 2-hr at 37 °C in water bath. Digested heart tissues were passed through a 40 μm cell strainer, grinded using a steel plunger and washed in cold-M buffer for five times. Then, the cell filtrate was centrifuged at 300 g for 5 min at room temperature. Cell pellet was re-suspended in 5 mL of incubation medium and counted using a haemocytometer prior to sorting using EasySep® Mouse CD117 (c-kit) selection cocktail (STEMCELL Technologies, Vancouver, Canada) and EasySep® Mouse haematopoietic Progenitor Cell Isolation Cocktail (STEMCELL Technologies, Vancouver, Canada) according to the manufacturer’s protocols. Due to CC heterogeneity, positively selected CCs were plated as 0.5 cells/well on 96-well plate to establish clonogenically-expanded CCs. The selected cell colonies with at least 20 cells were cultured on 1.5% (w/v) gelatin-coated (Sigma–Aldrich, St Louis, MO, USA) surface in cardiac cell complete growth medium (CGM) for subsequent clonogenic expansion. CGM was made up of two solutions: Solution 1 and Solution 2. Solution 1 comprised of DMEM/F12 containing 1% (v/v) insulin-transferrin-selenium, 1% (v/v) Penicillin-Streptomycin, 0.1% (v/v) fungizone and 0.1% (v/v) gentamicin. Solution 2 comprised of Neurobasal medium supplemented with 37 mg of L-glutamine, 2% (v/v) B27 supplement and 1% (v/v) N2 supplement. The complete growth medium was prepared by mixing the solutions in the ratio: 45% solution 1, 45% solution 2 and 10% (v/v) embryonic stem cell-qualified FBS (All the above were...
Bovine serum (FBS), 1 × Penicillin/streptomycin for initial 6 days of culture. On day 6, medium was changed to either 50 μg/mL ascorbic acid-supplemented medium or cardiogenic medium. Medium was changed every 2 days up to day 14. To decellularise the deposited ECM, the cultures were washed twice with PBS and treated with PBS containing 0.5% Triton X-100 and 20 mM NH₄OH for 5 min at 37 ºC. Lastly, the decellularised MSC ECM was treated with DNase for 30 min at 37 ºC. The ECM was washed with PBS, and stored at 4 ºC for up to 1 month.

2.5. Viability assay

Proliferation status of CCs were determined by using Presto Blue®. Briefly, CCs were seeded at 1500 cells/cm². Different cell numbers (2500, 5000, 10,000, 20,000 cells) were seeded to generate a relative standard curve to quantitate the exact cell number following 3 days of culture. 10% Presto Blue® in serum free medium was added into the culture and incubate for 1-h at 37 ºC. The value of fluorescence intensity was measure at 544 nm/590 nm with the use of microplate reader (BMG).

2.6. Oxidative stress assay

The CCs were seeded at 1500 cells/cm² for 5 days. Cell viability on day 5 was assessed using Presto Blue. The cells were then exposed to 100 μM hydrogen peroxide to induce stress on CCs. After 24-h exposure, CC viability was again assessed by Presto Blue. The value of fluorescence intensity was measure at 544 nm/590 nm with the use of microplate reader (BMG). The cell viability before and after exposure to hydrogen peroxide will be measured.

2.7. Chemical-induced CC cardiac differentiation

Cardiac cells were seeded at 10,000 cells/cm² in CC complete medium onto surface with or without ECM for 3 days. Thereafter, the medium was changed to cardiogenic medium [8] (Cardiogenic Medium was composed of α-MEM (Sigma–Aldrich, St Louis, MO, USA) supplemented with 10% (v/v) FBS, 1% (v/v) Penicillin-Streptomycin, 0.1% (v/v) gentamicin, 0.1% (v/v) Fungizone, 1 μM dexamethasone (Sigma–Aldrich, St Louis, MO, USA), 50 μg/mL ascorbic acid (Sigma–Aldrich, St Louis, MO, USA), and 1 mM β-glycerophosphate (Sigma–Aldrich, St Louis, MO, USA)) with medium change every 2 days. On day 21 after initiation of differentiation, RNA will be collected and assessed for cardiac markers gene expression (αMHC, βMHC, GATA4, NKX2.5, cTnI) and immunofluorescence staining (cTnI, SMA, VWF).

### Table 1

| Antibody                                           | Dilution Factor | Application   | Manufacturer                     |
|----------------------------------------------------|-----------------|---------------|----------------------------------|
| Rabbit Polyclonal Anti-c-kit Antibody (H-300)       | 1:50            | ICC/FC        | Santa Cruz Biotechnology, Germany (sc-5535) |
| Rabbit Polyclonal Anti-GATA-4 Antibody (H-112)      | 1:50            | ICC           | Santa Cruz Biotechnology, Germany (sc-9053) |
| Rabbit Polyclonal Anti-NKX2.5 Antibody (V-13)       | 1:50            | ICC           | Santa Cruz Biotechnology, Germany (sc-14033) |
| Goat Polyclonal Anti-Tryptase Antibody (V-13)       | 1:50            | ICC           | Santa Cruz Biotechnology, Germany (sc-32473) |
| Goat Polyclonal Anti-Sox2                          | 1:50            | ICC           | Santa Cruz Biotechnology, Germany (sc-17320) |
| Antibody (Y-17)                                    |                 | ICC           | Sigma Aldrich, USA (A2172)        |
| Mouse Monoclonal Anti-Smooth Muscle Actin (Clone 5CS) | 1:400           | ICC           | Dako, USA (A0082)                |
| Rabbit Polyclonal Anti-von Willebrand Factor Antibody | 1:400           | ICC           | Santa Cruz Biotechnology, Germany (sc-15368) |
| Rabbit Polyclonal anti-Cardiac Troponin T (H-170)  | 1:50            | ICC           | Molecular Probes, CA             |
| Alexa Fluor 488 Donkey Anti-rabbit Antibody         | 1:500           | ICC           | Molecular Probes, CA             |
| Alexa Fluor 488 Donkey Anti-goat Antibody           | 1:500           | ICC           | Molecular Probes, CA             |
| Alexa Fluor 568 Donkey Anti-rabbit Antibody         | 1:500           | ICC           | Molecular Probes, CA             |
| Alexa Fluor 568 Donkey Anti-goat Antibody           | 1:500           | ICC           | Molecular Probes, CA             |

Abbreviations: ICC — Immunocytochemistry; FC — Flow cytometry.
2.8. RNA extraction and cDNA conversion

Cells were harvested, and RNA was extracted using RNeasy Mini Kit (Qiagen) according to manufacturer’s protocol. RNA was stored at −80°C or used directly for cDNA conversion. To quantitate amount of RNA, 1 μl of sample was loaded onto Nanodrop (Thermo Fisher). 1 μg RNA was then reversed transcribed to cDNA by using QuantiTect Reverse Transcriptase kit (Qiagen) according to manufacturer’s protocol. cDNA was either use directly or stored at −80°C.

2.9. Quantitative real time PCR

Quantitative real time PCR (QPCR) was performed using Quantitative SYBR Green Kit (Qiagen) and the fluorescence intensity was measured by StepOne Plus (Applied Biosystem) according to manufacturers’ protocols. Briefly, a reaction master mix was prepared by mixing 10 μl of Quantitative SYBR Green PCR Master Mix, 2 μl of QN ROX reference dye, forward and reverse primer at final concentration of 0.7 μm each, and 50 ng of cDNA per one reaction. The cycling condition was i) PCR initial heat activation @95°C for 2 min, ii) 40 cycles of denaturation @95°C annealing/extension @60°C for 5 s and combined annealing/extension @60°C for 10 s, iii) Melting curve analysis. The final Ct value was normalised to housekeeping gene and fold changes were analysed using comparative Ct value to a suitable control. Primers were listed in Table 2.

2.10. Data analysis

All data were expressed as mean ± standard error of mean (SEM). All statistical analyses were performed using SPSS (IBM SPSS Statistics 22). The differences between groups were analysed using independent t-test and One-way ANOVA with Tukey post-hoc test and is considered significant when p < 0.05.

3. Results

3.1. Isolation and characterisation of cardiac c-kit cells

Cardiac c-kit cells isolated from magnetic-associated cell sorting were characterised by immunocytochemistry staining. Cardiac c-kit cells were positive for c-kit, expressed cardiac differentiation for 21 days showed expression of cardiac troponin I (cTnI), smooth muscle actinin (SMA) and endothelial marker (vWF) (Fig. 1b).

| Gene/Accession Number | Primer Sequence (5’-3’) |
|-----------------------|-------------------------|
| GATA4                 | Forward: TCTTGCATGTCGCCATAACCA |
| NM_008092.3           | Reverse: TGGTTGCTAGGCTGAAAAA |
| Nkx2.5                | Forward: GCTACAAGTACAGCCGACAG |
| NM_008700.2           | Reverse: GGCTCGGCTGATTACATA |
| nMHC                  | Forward: AAGCTGAGGCGTACAGG |
| NM_010856.4           | Reverse: GGTCTCCTGGAGAGGTTATTCC |
| βMHC                  | Forward: GGAACACCAAAACCTGTCAGAAGTCC |
| NM_080728.2           | Reverse: TGCCGGCTCCCGGAGGAGG |
| cTnI                  | Forward: ACCCAAGACCTGCTGAGG |
| NM_0003531.4          | Reverse: ACCCAAGACCTGCTGAGG |
| GAPDH                 | Forward: CACATCGGGGCTGAACAC |

Table 2 Primer list used in this study.

3.2. Decellularisation of MSC-derived matrices

MSCs were cultured in medium containing ascorbic acid on day 6 until day 14 until it reached full cell confluency and morphology on day 14 prior to decellularisation (Fig. 2a). As SDS has been widely used to decellularise organ in tissue engineering study [19], we first decellularised confluent MSCs (Fig. 2b) in 2D culture on day 14 with SDS/Triton X-100 (ST). Complete cell removal was observed, but with no ECM retaining on the surface. To circumvent this, we substituted SDS with ammonia, which is a milder detergent as compared to SDS for decellularisation. Although matrix delamination was still observed following AT treatment, 30 ± 1% of the wells with ECM on the surface was observed as compared to ST (p < 0.001) (Fig. 2c). Overall, these results indicated that AT is a better detergent as compared to ST in decellularising cell-derived matrices.

3.3. MSC-matrix retention after cell decellularisation in 2-dimensional culture

Dexamethasone-based medium have been proposed to be able to direct cardiac cell differentiation towards cardiac lineages [3]. Therefore, as culture medium may affect ECM secretion we cultured MSCs in dexamethasone-based cardiogenic medium instead of ascorbic-acid supplemented medium to induce deposition of matrices that mimicking cardiomyocyte microenvironment. Interestingly, we observed 92 ± 5% of wells retaining matrices on the surface following decellularisation using AT, as shown in Fig. 2e (p < 0.001 vs. ascorbic acid). Protein quantification confirmed the presence of higher protein level in cardiogenic- ECM (ECMCardio) than ascorbic acid-treated ECM (ECMAscorbic acid) (10.4 ± 0.8 μg/ml vs. 1.9 ± 0.2 μg/ml, p < 0.01) (Fig. 2f). The difference between ECMAscorbic acid and ECMCardio was that ECMCardio preserved the ultrastructure of MSCs and retained higher ECM protein on the surface as demonstrated in Fig. 2d. Taken together, these results suggest that ECM retention was dependant on decellularisation technique and induction medium for ECM deposition.

3.4. The effects of MSC-derived ECM on CC proliferation and resistance to oxidative stress

To elucidate if ECMAscorbic acid or ECMCardio improved CC proliferation, we seeded the cells on the ECM and cultured for 3 days. We found that the cells culturing on ECM did not showed any improvement in CC proliferation as compared to CCs cultured without ECM (Fig. 3a) (77.552 ± 802 on ECMCardio vs. 86.312 ± 3201 cells on ECMAscorbic acid, p > 0.05). Highest cell viability was found on CC cultured on ECMCardio following exposure to 100 μM hydrogen peroxide (H2O2) for 24 h in serum free condition (67.2 ± 0.7%, p < 0.05 vs. control), followed by ECMAscorbic acid (Fig. 3b) (47.1 ± 0.9%, p < 0.05 vs. control) and control (42.9 ± 5.0%). These results suggest that ECM confers CC resistance towards exogenous oxidative stress.

3.5. The effects of MSC-derived ECs on CC cardiomyocyte differentiation

Next, cardiac differentiation of CCs was tested after cultured on both ECs after differentiated using dexamethasone-based medium for 21 days. Immunocytochemistry showed that the differentiated cells were positive for cardiac troponin I, smooth muscle and endothelial cells for all the groups with or without ECM (Fig. 4a). Gene expression analysis showed up-regulation in cMHC (1.2-fold, p < 0.05 vs. control) and cTnI (1.8-fold, p < 0.05 vs. control)
genes in CCs after cultured on ECM\textsuperscript{cardio} (Fig. 4b). CCs cultured on ECM\textsuperscript{MA} also exhibited up-regulation of cTnI (1.6-fold, p < 0.05 vs. control) gene expression. No significant differences were observed for \(\alpha\)MHC, GATA4 and NKX2.5 gene expressions among groups.

4. Discussions

Cardiac cell therapy has been proven to be a promising strategy for treating patients with myocardial infarction [4,33]. However, cellular therapy is often limited by low cell number, poor cell engraftment and cell differentiation post transplantation [6,14]. Following myocardial infarction, infarcted region was replaced by scar tissue, which also involves changes in extracellular matrices [34]. These deleterious events could limit cell engraftment and viability post-transplantation. Decellularised extracellular matrix (ECM) obtained by removal of cellular components, has recently emerged as a cell culture technology for maintaining primary cell phenotype during expansion. Decellularised ECM can be obtained from in vivo tissue ECM or ECM fabricated by cells cultured in vitro. The ECM is composed of many types of collagens, proteoglycans, glycoproteins, and glycosaminoglycans that form a complex structure [35]. The protein components of the ECM vary for different tissues and organs [36] and the composition of the ECM is determined by developmental and pathological conditions [34,37].

In this study, MSCs were cultured on plastic surface in normal growth medium for 6 days, and changed the medium to normal growth medium supplemented with ascorbic acid to increase the ECM deposition from cells [38,39]. Sodium dodecyl sulphate (SDS) is an ionic detergent which has been widely used in decellularising organs ECM to solubilise both nuclear and cytoplasmic cellular membranes [19]. In this study SDS was combined with Triton X-100 (ST), a non-ionic surfactant which offers only mild decellularization effects on tissue structure [40]. However with ST, matrices were delaminated from the well surface, attributed to SDS which potentially compromised the ECM content and mechanical strength [41], and thus not suitable for decellularization on 2D cell monolayer. Ammonium hydroxide is another mild detergent which have been reported to efficiently decellularising cell-derived ECM [22,42–44]. Decellularization by substituting ST with AT yielded 30% of wells with matrix retention on plastic surface. However, the matrix ultrastructure following AT treatment was distorted despite having intact protein matrices on the surface, of which also prone to delamination after washing. Strategy to minimize delamination following 2-D culture decellularisation includes coating with ethanolamine- [23,45], or fibronectin [42,46] to chemically rigidify the prepared matrices. However, coating with another ECM may alter the composition of secreted ECM, MSC and CC functions, and thus affects the interpretation of the results in this study. Nonetheless, we resolved it by culturing the MSCs in the cardiogenic medium containing dexamethasone, ascorbic acid, and \(\beta\)-glycerolphosphate for 14 days, with high rates of matrix retention on the wells was observed. This result suggests that choice of culture medium and decellularisation technique affect the quality of produced ECM.

Previous research determined that the ECM influences stem cell differentiation and the maintenance of stemness [47,48]. Decellularized matrices from MSCs cultured in osteogenic- or adipogenic-stimulating medium have shown to improves its osteogenesis and
adipogenesis [49], suggesting that the stimulation also induces secretion of specific ECM that facilitates specific differentiation process. Although MSC-ECM has been shown to improve proliferation and differentiation of cultured adult MSCs [44], proliferation was not seen in CCs cultured on cardiogenic ECM in this study. This propose that the secreted matrices were more likely to be pro-differentiation than pro-proliferation.

Oxidative stress has been observed in the heart following myocardial infarction (10–12). Although cells exhibit antioxidant system that could minimise the effect of ROS, the deregulation of the antioxidant-oxidant systems can result in decompensated cardioprotective effect (13, 14). H$_2$O$_2$ has been demonstrated to increase reactive oxygen species (ROS) in cells [15,16]. The increased ROS level can damage cell membranes and cellular constituents, which then lead to cell death [17,18]. Here, we observed MSC-ECM confers CC resistance to exogenous H$_2$O$_2$, showing higher cell viability compared to control, a similar observation with a previous study [23]. Future study will examine if the observed
The effect is due to the capability of MSC-ECM in modulating H₂O₂ degradation in and redox signalling in CCs, as seen in endothelial cells (15), the role of PI3K/Akt signalling (16) or the influence in caspase 8 and 9 activities that dictate the apoptosis and necrosis of CCs (17).

Recently, the identity and cardiac commitment of endogenous cardiac c-kit cells has been questioned and hugely debated, which begins with a study by van Berlo et al. (2014) who challenged the cardiac commitment of c-kit cells through tracked the development of c-kit cells in the growing heart using Kit-Cre lineage tracing in mice [50]. They found that only 0.03% of the endogenous c-kit cells become cardiomyocytes, and number may reduce to 0.008% if cell fusion event is considered [50]. Majority of the c-kit was found to be CD31⁺ endothelial cells. The same conclusion was also drawn from two independent studies [51,52]. However, a study argued that myogenic cardiac c-kit cells express low yet detectable c-kit
mRNA and protein, the low level of Cre expression in the c-kit cells from KitCre knock-in mice could affect the efficiency ofloxP recombination, and thus question the capability of the system in identifying the myogenic c-kit population [53]. These myogenic c-kit cells are single-cells derived clones from the cohort of lineage negative CD45 negative population, which constitute only 1–2% of the total c-kit myocardial cells, with only 10% of them can robustly alternate and further upregulated the cardiac gene expressions, offering an solution, and AT is a better decellularising agent than ST in this instance. ECMc-kit protects CCs from exogenous oxidative stress and further upregulated the cardiac gene expressions, offering an alternate in vitro priming strategy to precondition CCs which could potentially enhance its survival and function after in vivo transplantation.

In conclusions, the retention of MSC-secreted ECM in 2D culture may be affected by culture medium and decellularisation solution, and AT is a better decellularising agent than ST in this instance. ECMc-kit protects CCs from exogenous oxidative stress and further upregulated the cardiac gene expressions, offering an alternate in vitro priming strategy to precondition CCs which could potentially enhance its survival and function after in vivo transplantation.

Conflicts of interest

J JT received a research grant from CryoCord Sdn Bhd. All funders do not involve in conceiving the experimental design and data analysis of this project. Others declare no conflict of interest.

Author contribution

JJT conceived research design, WHN performed the experiments, analysed data and drafted the manuscript. JJJT, BS, SHN, YKY and RR interpreted and analysed data. JJT, BS revised, proofread and approved the final draft manuscript.

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References

[1] Beltrami AP, Barlucchi L, Torella D, Baker M, Limana F, Chimenti S, et al. Adult cardiac stem cells are multipotent and support myocardial regeneration. Cell 2003;114(6):763–76.

[2] Bearzi C, Rota M, Hosoda T, Tillmanns J, Nascimbene A, De Angelis A, et al. Isolation and expansion of adult cardiac stem cells from human and murine cardiomyocytes: an in vitro model for studying human cardiac physiology and pathophysiology. Nat Protoc 2008;12(1):10–49.

[3] Beltrami AP, Rota M, Hosoda T, Tillmanns J, Nascimbene A, De Angelis A, et al. Characterization of resident endogenous c-Kit+ cardiac stem cells from the adult mouse and rat heart. Nat Protoc 2009;4(7):1662–81.

[4] Beltrami AP, Rota M, Hosoda T, Tillmanns J, Nascimbene A, De Angelis A, et al. Characterization of resident endogenous c-Kit+ cardiac stem cells from the adult mouse and rat heart. Nat Protoc 2009;4(7):1662–81.

[5] Beltrami AP, Rota M, Hosoda T, Tillmanns J, Nascimbene A, De Angelis A, et al. Characterization of resident endogenous c-Kit+ cardiac stem cells from the adult mouse and rat heart. Nat Protoc 2009;4(7):1662–81.

[6] Beltrami AP, Barlucchi L, Torella D, Baker M, Limana F, Chimenti S, et al. Adult cardiac stem cells are multipotent and support myocardial regeneration. Cell 2003;114(6):763–76.

[7] Beltrami AP, Barlucchi L, Torella D, Baker M, Limana F, Chimenti S, et al. Adult cardiac stem cells are multipotent and support myocardial regeneration. Cell 2003;114(6):763–76.

[8] Beltrami AP, Barlucchi L, Torella D, Baker M, Limana F, Chimenti S, et al. Adult cardiac stem cells are multipotent and support myocardial regeneration. Cell 2003;114(6):763–76.
Manabe R, Tsutsui K, Yamada T, Kimura M, Nakano I, Shimono C, et al. Transcriptome-based systematic identification of extracellular matrix proteins. Proc Natl Acad Sci U S A 2008;105(35):12849–54.

Bonnans C, Chou J, Werb Z. Remodeling the extracellular matrix in development and disease. Nat Rev Mol Cell Biol 2014;15(12):786–801.

Wu Y, Puperi DS. Ascorbic acid promotes extracellular matrix deposition while preserving valve interstitial cell quiescence within 3D hydrogel scaffolds. J Tissue Eng Regenerat Med 2017;11(7):2316–24.

Gilbert TW. Strategies for tissue and organ decellularization. J Cell Biochem 2012;113(7):2217–22.

Xing Q, Yates K, Talbinten M, Shearier E, Qian Z, Zhao F. Decellularization of fibroblast cell sheets for natural extracellular matrix scaffold preparation. Tissue Eng C Methods 2015;21(1):77–87.

Prewitz MC, Seib FP, von Bonin M, Friedrichs J, Stiszel A, Niehage C, et al. Tightly anchored tissue-mimetic matrices as instructive stem cell microenvironments. Nat Methods 2012;10(8):788–94.

Lu H, Hoshiba T, Kawazoe N, Chen G. Comparison of decellularization techniques for preparation of extracellular matrix scaffolds derived from three-dimensional cell culture. J Biomed Mater Res A 2012;100(9):2507–16.

Ng CP, Mohamed Sharif AR, Heath DE, Chow JW, Zhang CPY, Chan-Park MB, et al. Enhanced ex vivo expansion of adult mesenchymal stem cells by fetal mesenchymal stem cell ECM. Biomaterials 2014;35(13):4046–57.

Franco-Barraza J, Beacham DA, Amatangelo MD, Cukierman E. Preparation of extracellular matrices produced by cultured and primary fibroblasts. In: Curr protoc cell biol. John Wiley & Sons, Inc.; 2001. https://doi.org/10.1002/cpb.2.

Kusuma GD, Bremnecke SP, O’Connor AJ, Kalionis B, Heath DE. Decellularized extracellular matrices produced from immortal cell lines derived from different parts of the placenta support primary mesenchymal stem cell expansion. PloS One 2017;12(2):e0171488.

Bi Y, Ehrichou D, Kilts TM, Inkson CA, Embree MC, Sonoyama W, et al. Identification of tendon stem/progenitor cells and the role of the extracellular matrix in their niche. Nat Med 2007;13(10):1219–27.

Bi Y, Stuelten CH, Kilts T, Wadhwa S, Iozzo RV, Robey PG, et al. Extracellular matrix proteoglycans control the fate of bone marrow stromal cells. J Biol Chem 2005;280(34):30481–9.

Hoshiba T, Kawazoe N, Tateishi T, Chen G. Development of stepwise osteogenesis-mimicking matrices for the regulation of mesenchymal stem cell functions. J Biol Chem 2009;284(45):31164–73.

van Berlo JH, Kanissacak O, Maillet M, Vagnozzi RJ, Karch J, Lin SC, et al. c-kit(-) cells minimally contribute cardiomyocytes to the heart. Nature 2014;509(7500):337–41.

Sultana N, Zhang L, Yan J, Chen J, Cai W, Razzaque S, et al. Resident c-kit(+) cells in the heart are not cardiac stem cells. Nat Commun 2015;6:8701.

Liu Q, Yang R, Huang X, Zhang H, He L, Zhang L, et al. Genetic lineage tracing identifies in situ Kit-expressing cardiomyocytes. Cell Res 2016;26(1):119–30.

Vicinanza C, Aquila I, Gianfalone E, Scalise M, Marino F, Mancuso T, et al. Kit(cre) knock-in mice fail to fate-map cardiac stem cells. Nature 2018;555(7697):e1–5.

Chugh AR, Beache GM, Loughran JH, Meivon N, Elmore JB, Kajstura J, et al. Administration of cardiac stem cells in patients with ischemic cardiomyopathy: the SCIPio trial: surgical aspects and interim analysis of myocardial function and viability by magnetic resonance. Circulation 2012;126(11 Suppl 1):S54–64.