

治験でヒトに使用する前に製品の安全性と品質の「確認」を厚生労働大臣に求める過程（確認申請）が必要とされていた。ただし、確認申請は手続きに時間がかかることが難点とされるなどの理由で平成23年に廃止され、現在はこれに代わる制度として医薬品・医療機器薬事戦略相談（薬事戦略相談）が導入されている。薬事戦略相談は、医薬品医療機器総合機構（PMDA）が細胞・組織加工製品等の先端的医薬品・医療機器の開発初期段階から、品質・安全性に係る相談を受け付けて、薬事承認に向けて必要な試験の詳細などを対面助言するものであり、治験・製品開発の迅速化に向けた今後の運用が注目される。

細胞・組織加工製品は、薬事法上の取扱い方法の分類からすれば「特定生物由来製品」とみなされる可能性が他の製品よりも高く、そうなれば保健衛生上の危害の発生または拡大を防止するための措置を講ずることが必要となってくる。また、先端的製品であるために臨床使用経験や情報の蓄積が乏しく、製品の態様も多種多様であることから、リスクの判断が難しい。したがって細胞・組織加工製品の開発においては、規制当局が評価基準を作成し、研究開発を実施する企業・研究者のみならず審査官に対しても適用することにより、評価基準に対する理解を各者が共有することが重要である。表にそれらの評価基準を含む、再生医療に係わる通知・指針等を示す。現在わが国には、細胞・組織加工製品の品質・安全性確保についての主幹となるガイドラインとして、①「細胞・組織利用医薬品等の取扱い及び使用に関する基本的考え方」（以下「基本的考え方」）、②「ヒト（自己）由来細胞・組織加工医薬品等の品質及び安全性の確保に関する指針」（以下「ヒト自己製品指針」）および③「ヒト（同種）由来細胞・組織加工医薬品等の品質及び安全性の確保に関する指針」（以下「ヒト同種製品指針」）がある。「基本的考え方」は、細胞・組織を取り扱う際の基本的要件を示すとともに、細胞・組織加工製品の品質・安全性、並びに細胞・組織の取扱いに関する科学的および倫理的妥当性を確保することを目的とし、細胞・組織加工製品の承認後のみならず、治験時においても適用される。「基本的考え方」の中で細胞・組織加工製品の安全性に関して最も強調されているのは、細菌、真菌、ウイルス等の汚染の危険性への対策である。なお、日本

のGTP (good tissue practice) は、「基本的考え方」と「生物由来原料基準」(表)とで形成されている。「ヒト自己製品指針」および「ヒト同種製品指針」は、それぞれヒト（自己）由来およびヒト（同種）由来の細胞・組織加工製品の品質および安全性確保のための基本的な技術要件についてまとめたもので、製造販売承認申請時にのみならず、治験開始の際に求められる資料について記されている。ヒト（自己）由来製品とヒト（同種）由来製品との間の根本的な差異は、自己由来の細胞・組織を用いる場合には、その細胞・組織を介する感染症伝播のリスクおよび免疫学的な問題が理論上ないことである。しかし、自己由来であっても製造工程におけるクロスコンタミネーションの問題や、製造従事者・医療従事者等の安全上の問題は同種由来の場合と同様に存在する。また、培養工程においてウイルスが増殖するリスクを考慮することが必要な場合もある。さらに、自己由来の場合、個別製品の製造となるので、それらの品質のばらつきを最小限にとどめる工夫が必要な反面、製品レベルでの各種試験の実施に試験検体の量的制約がある。それらに留意した合理的な品質確保の方策（製造工程のより厳密な恒常性維持・管理など）を採用する必要がある。また、自己由来であっても、遺伝子改変細胞の場合には相応の留意が必要である。なお、近年その研究成果が注目されているヒト体性幹細胞、ヒト胚性幹細胞（ES細胞）、ヒト人工多能性幹細胞（iPS細胞）等のヒト幹細胞を加工した製品については、より早期に実用化するために、これらに特化した留意事項について記した指針案が最近作成されており^{2)～6)}、近日中に最終的な指針が公表される予定となっている。

承認申請時に厚生労働大臣に提出する非臨床安全性試験の結果は、GLP (good laboratory practice ; 表) を遵守し信頼性が確保されたものであることが原則であるが、治験開始に際して提出する非臨床安全性試験データは、必ずしもGLPに従って取得されたものである必要はない。ただし、最終的に承認申請時にはGLPに従っていることが求められるので、治験計画提出時に準備しておくことによって試験の重複を省くことができる。

表 再生医療/細胞・組織加工製品の開発に係わる主な省令、通知、指針等

文書名	初版/最新版(平成24年1月現在)	備考
ヒト幹細胞を用いる臨床研究に関する指針	平成18年7月3日厚生労働省告示第425号/平成22年11月1日厚生労働省告示第380号	ヒト幹細胞臨床研究が社会の理解を得て、適正に実施・推進されるよう、個人の尊厳と人権を尊重し、かつ、科学的知見に基づいた有効性及び安全性を確保するための指針。
生物由来原料基準	平成15年5月20日厚生労働省告示第210号/平成17年3月31日厚生労働省告示第177号	医薬品、医薬部外品、化粧品及び医療機器に使用されるヒトや動物に由来する原料又は材料について、製造に使用される際に講ずべき必要な措置に関する基準を定めることにより、医薬品等の品質、有効性及び安全性を確保することを目的とする。
細胞・組織利用医薬品等の取扱い及び使用に関する基本的考え方	平成12年12月26日医薬発第1314号別添1	「生物由来原料基準」と併せてGTPを形成する、細胞・組織を取り扱う際の基本的要件を示すとともに、細胞・組織を利用した製品の品質・安全性、並びに細胞・組織の取扱いに関する科学的及び倫理的妥当性を確保することを目的とする。
ヒト(自己)由来細胞や組織を加工した医薬品又は医療機器の品質及び安全性の確保に関する指針	平成20年2月8日薬食発第0208003号	ヒト細胞・組織を加工した医薬品又は医療機器について品質及び安全性の確保のための基本的な技術要件について定めたもの、細胞提供者が自己(患者本人)の場合と同種(他人)の場合を区別して整理し、それぞれの注意事項をまとめている。
ヒト(同種)由来細胞や組織を加工した医薬品又は医療機器の品質及び安全性の確保に関する指針	平成20年9月12日薬食発第0912006号	
医薬品の安全性に関する非臨床試験の実施の基準に関する省令	平成9年3月26日厚生省令第21号/平成20年厚生労働省令第114号	GLP省令、非臨床試験施設の構造設備、標準操作手順書の作成、動物の管理、プロトコルや最終報告書の作成などを規定、承認申請時に提出する非臨床安全性試験の結果はGLPに従っていることか原則。
医療機器の安全性に関する非臨床試験の実施の基準に関する省令	平成17年3月23日厚生労働省令第37号/平成20年厚生労働省令第115号	
医薬品及び医薬部外品の製造管理及び品質管理の基準に関する省令	平成16年12月24日厚生労働省令第179号	GMP省令、医薬品及び医薬部外品の製造販売承認の要件として、医薬品及び医薬部外品の製造所における製造管理・品質管理の基準を定めたもの。
医療機器及び体外診断用医薬品の製造管理及び品質管理の基準に関する省令	平成16年12月17日厚生労働省令第169号	QMS省令(医薬品のGMP省令に相当)、医療機器及び体外診断用医薬品の製造販売承認の要件として、医療機器及び体外診断用医薬品の製造所における製造管理・品質管理の基準を定めたもの。
治験薬の製造管理、品質管理等に関する基準(治験薬GMP)	平成20年7月9日薬食発第0709002号別添	治験薬GMP、企業から提供を受けた医薬品を治験薬として取り扱う際の製造管理・品質管理等の基準。
ヒト(自己)細胞・組織加工医薬品等の製造管理・品質管理の考え方について	平成20年3月27日薬食監麻発第0327025号	ヒト自己由来細胞・組織加工製品のGMP、患者本人から直接細胞・組織を採取するという特殊性等を踏まえた製造管理・品質管理の考え方。
医薬品の臨床試験の実施の基準に関する省令	平成9年3月27日厚生省令第28号/平成21年3月31日厚生労働省令第68号	GCP省令、治験を依頼する者、治験を自ら(医師主導治験)実施しようとする者に係る「治験の準備に関する基準」及び「治験の管理に関する基準」、治験を実施する医療機関が行うべき「治験を行う基準」などを定めたもの。
医療機器の臨床試験の実施の基準に関する省令	平成17年3月23日厚生労働省令第36号/平成21年3月31日厚生労働省令第68号	

4 治験の科学的信頼性・安全性確保と倫理的実施に関する規制・制度

薬事法では、治験を依頼する者(企業主導治験)、治

験を自ら実施しようとする者(医師主導治験)は、厚生労働大臣に治験計画を届け出なければならないと定めている。治験はこの計画の届け出後30日過ぎないと実施できない。治験計画に問題があり開始を中止する

必要がある場合には、この30日の間に厚生労働省からその旨の指示がある。

細胞・組織加工製品を含む医薬品・医療機器の治験は、「ヒトを対象とした医学研究のための倫理規定」いわゆる「ヘルシンキ宣言」で言う「ヒトを対象とした医学研究」であり、治験に参加する者の人権と安全の確保が絶対条件である。また、科学的に適切に設計されたものであることも不可欠である。承認申請時に厚生労働省に提出する治験データは、GCP省令(表)と呼ばれる治験の取扱い基準に適合するものでなければならない。

GCP省令には、治験を依頼する者、治験を自ら実施(医師主導治験)しようとする者に係る「治験の準備に関する基準」および「治験の管理に関する基準」、治験を実施する医療機関が行うべき「治験を行う基準」などが定められており、プロトコルの妥当性、被験者の安全性・個人情報保護、倫理性などを確保しつつ、科学的に適正で信頼性の高い試験データが得られるように臨床試験を行うための基準となっている。

平成20年に出された内閣府規制改革会議第三次答申には、再生医療関連にも多くの指摘事項があった。これを受けて厚生労働省は平成21・22年度に「再生医療における制度的枠組みに関する検討会」を設置した。その報告書の1つ「再生・細胞医療に関する臨床研究から実用化への切れ目ない移行を可能とする制度的枠組みについて」⁷⁾には、わが国のGCP省令は国際的に調和されたICH-GCPに基づいているが、その運用面においては欧米と比べて負担が多いとの指摘があること、厚生労働省では治験契約の規定の見直しなどその改善を図ってきたこと、並びに今後とも治験の実施状況を見つつ必要な改善を検討していくことが必要であることなどが述べられている。質の高い細胞・組織加工製品を迅速に開発する方策として今後どのように治験の制度・運用を改善すべきか、動向を注目しながら幅広い議論を行うことが必要だと考えられる。

おわりに

ヒトES細胞を原材料とする世界初の製品の臨床試験を実施していた米国Geron社は、平成23年11月に臨床試験の中止に加え、再生医療事業からの撤退を発表した。その理由として、高コストの問題と規制の問題(規制の複雑さとそれによるコストへの影響など)を挙げている。国内においても、再生医療事業を行うバイオベンチャー企業にとって規制の壁は高いとされ、新たな製品の開発は苦戦を強いられており、撤退を余儀なくされる企業が後を絶たない。また、日本の治験は海外よりさらに高コストであるため、臨床試験の実施・販売承認取得を最初に海外、特に欧米でめざすケースが多くなっている。自国産の製品・技術の恩恵をいち早く国内の患者・国民が享受できないという事態は憂慮すべき問題である。その解決には産・官・学だけでなく「医療現場」と「患者・国民」を含めたすべての関係者が協力し、「両期的な細胞・組織加工製品を治療を待ち望む患者さんのもとに届ける」という共通の目標に向かって治験等の制度・運用を改善する努力を続けることが必要だと考えられる。

文献

- 1) 「新たな治験活性化5カ年計画」について
<http://www.mhlw.go.jp/shingi/2007/03/s0330-5.html>
- 2) 早川堯夫ほか：再生医療，10：91-98，2011
- 3) 早川堯夫ほか：再生医療，10：107-117，2011
- 4) 早川堯夫ほか：再生医療，10：99-106，2011
- 5) 早川堯夫ほか：再生医療，10：118-128，2011
- 6) 早川堯夫ほか：再生医療，10：129-140，2011
- 7) 医政発0428第7号・薬食発0428第1号厚生労働省医政局長・医薬食品局長通知別添1
http://www.mhlw.go.jp/bunya/iryuu/dl/tuuti_230428.pdf

<筆頭著者プロフィール>

草川森士：先端医療振興財団・研究員、明治大学農学部卒、東京大学大学院医学系研究科修了。博士(医学)。国立成育医療研究センター研究所・研究員を経て、平成23年より現職。専門は幹細胞生物学、神経科学。現在、幹細胞の分化の研究を行うとともに、国立医薬品食品衛生研究所の協力研究員として「多能性幹細胞安全情報サイト」(URL：<http://www.nihs.go.jp/cgtp/cgtp/sec2/sispsc/html/index.html>)の運営に携わっています。

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GRK6 deficiency in mice causes autoimmune disease due to impaired apoptotic cell clearance

Michio Nakaya¹, Mitsuru Tajima¹, Hidetaka Kosako², Takeo Nakaya³, Akiko Hashimoto¹, Kenji Watari¹, Hiroaki Nishihara¹, Mina Ohba¹, Shiori Komiya¹, Naoki Tani², Motohiro Nishida¹, Hisaaki Taniguchi², Yoji Sato⁴, Mitsuru Matsumoto⁵, Makoto Tsuda⁶, Masahiko Kuroda³, Kazuhide Inoue⁶ & Hitoshi Kurose¹

Efficient engulfment of apoptotic cells is critical for maintaining tissue homeostasis. When phagocytes recognize 'eat me' signals presented on the surface of apoptotic cells, this subsequently induces cytoskeletal rearrangement of phagocytes for the engulfment through Rac1 activation. However, the intracellular signalling cascades that result in Rac1 activation remain largely unknown. Here we show that G-protein-coupled receptor kinase 6 (GRK6) is involved in apoptotic cell clearance. GRK6 cooperates with GIT1 to activate Rac1, which promotes apoptotic engulfment independently from the two known DOCK180/ELMO/Rac1 and GULP1/Rac1 engulfment pathways. As a consequence, GRK6-deficient mice develop an autoimmune disease. GRK6-deficient mice also have increased iron stores in splenic red pulp in which F4/80⁺ macrophages are responsible for senescent red blood cell clearance. Our results reveal previously unrecognized roles for GRK6 in regulating apoptotic engulfment and its fundamental importance in immune and iron homeostasis.

¹Department of Pharmacology and Toxicology, Graduate School of Pharmaceutical Sciences, Kyushu University, Fukuoka 812-8582, Japan. ²Division of Disease Proteomics, Institute for Enzyme Research, University of Tokushima, Tokushima 770-8503, Japan. ³Department of Molecular Pathology, Tokyo Medical University, Tokyo 160-8402, Japan. ⁴Division of Cellular and Gene Therapy Products, National Institute of Health Sciences, Setagaya, Tokyo 158-8501, Japan. ⁵Division of Molecular Immunology, Institute for Enzyme Research, University of Tokushima, Tokushima 770-8503, Japan. ⁶Molecular and System Pharmacology, Graduate School of Pharmaceutical Sciences, Kyushu University, Fukuoka 812-8582, Japan. Correspondence and requests for materials should be addressed to H.K. (email: kurose@phar.kyushu-u.ac.jp).

During animal development and in immune responses, numerous harmful and unnecessary cells are generated. These cells undergo apoptosis and are rapidly engulfed by phagocytes such as macrophages and dendritic cells. When an engulfment system does not function adequately, dying cells accumulate and undergo secondary necrosis that results in the release of noxious cellular components into the extracellular space. These released self-antigens are considered to induce lymphocyte activation and autoantibody production, which results in the development of autoimmune diseases such as systemic lupus erythematosus (SLE). Thus, the efficient clearance of apoptotic cells is indispensable for maintaining tissue homeostasis. Apoptotic cell removal is supposedly triggered by the release of 'find me' signals such as nucleotides and lipids from dying cells¹. These signals recruit phagocytes to the apoptotic cells. Subsequently, the recruited phagocytes recognize 'eat me' signals on the surface of apoptotic cells through the corresponding phagocyte receptors². This receptor recognition then elicits signals that induce cytoskeletal rearrangements for encapsulating the apoptotic cells³.

To date, a variety of ligands on apoptotic cells and their corresponding receptors on phagocytes have been proposed to be involved in this recognition process⁴. Two conserved intracellular pathways, CrkII/DOCK180/ELMO/Rac1 and GULP/Rac1, are well known to be involved in cytoskeletal rearrangements for apoptotic cell engulfment^{5–7}. However, molecules downstream of phagocytic receptors that are required for ingesting apoptotic cells still remain much to be determined.

G-protein-coupled receptor kinase 6 (GRK6) is a member of the GRK superfamily. GRKs were initially identified as molecules that phosphorylate G-protein-coupled receptors (GPCRs) and result in their desensitization^{8–10}. When GPCRs are activated by binding to their cognate ligands, GRKs recognize these activated receptors and phosphorylate them. Then, β -arrestins bind to these phosphorylated receptors, which block further stimulation of G-proteins by the agonist-bound receptors through steric hindrance¹¹. In addition to regulating GPCR desensitization, recent evidence indicates that GRKs have roles in cellular signalling independently of the GPCR-mediated pathways by phosphorylating non-GPCR substrates^{12,13}. For example, GRK2 and GRK5 phosphorylate IRS1 and HDAC5, respectively^{14,15}. Although numerous *in vitro* studies have established the importance of GRKs for regulating GPCR signalling and phosphorylating non-GPCR proteins, the physiological and pathological roles of GRKs, including GRK6, *in vivo* remain poorly understood.

Here we demonstrate a previously unknown function for GRK6 in apoptotic cell clearance. GRK6 enhances apoptotic cell engulfment through Rac1 activation, an indispensable molecule involved in engulfment signalling. In addition, we show that this GRK6-mediated engulfment depends on GIT1¹⁶ and phosphorylation of radixin and moesin¹⁷, both of which have been implicated in membrane skeleton organization. GRK6-deficient macrophages exhibited impaired phagocytosis of apoptotic cells. Consequently, GRK6-deficient mice developed an autoimmune condition similar to those of mice with other knocked-out molecules involved in apoptotic engulfment. We also found that GRK6 was highly expressed in red splenic macrophages responsible for removing senescent red blood cells. GRK6 significantly contributed to their clearance, as GRK6-deficient mice had increased iron stores because of the inefficient iron uptake in the red pulp of their spleens. Our results establish that GRK6 is a critical factor for regulating immune and iron homeostasis.

Results

GRK6 is involved in the engulfment of apoptotic cells. To examine the possible involvement of GRK family members in the

engulfment of apoptotic cells, we first examined the effects of GRKs on the engulfment by NIH3T3 cells. NIH3T3 is a mouse embryonic fibroblast cell line, although these cells can engulf apoptotic thymocytes. In addition, the efficiency of retroviral gene transfer to these cells is >90%. Thus, we used NIH3T3 cells as phagocytes in our experiments. Among the seven GRKs, some GRK (GRK1, 4 and 7) expressions are restricted to certain tissues, whereas other GRKs (GRK2, 3, 5 and 6) are widely expressed¹⁸. Thus, we introduced kinase-inactive and dominant-negative (DN) mutants¹⁹ of GRK2, 3, 5 and 6 (GRK2 (K220R), GRK3 (K220R), GRK5 (K215R) and GRK6 (K215R)) into NIH3T3 cells and determined the effect of each mutant on NIH3T3 cells' engulfment capacity. Virally infected NIH3T3 cells were co-cultured with fluorescently labelled apoptotic thymocytes at 37 °C for 90 min. After co-culture, the fluorescence uptake by NIH3T3 cells was evaluated by flow cytometry. As shown in Fig. 1a, 18% of the vector-expressing NIH3T3 cells engulfed apoptotic cells under these experimental conditions. Among the four kinase-inactive and DN GRK mutants, only GRK6 (K215R) significantly attenuated apoptotic cell engulfment by NIH3T3 cells, which indicated that GRK6 kinase activity was important for efficient engulfment (Fig. 1a). Knockdown of GRK6 by small interfering RNA (siRNA) treatment (about 70% reductions in the GRK6 protein level) also reduced the engulfment by NIH3T3 cells (Fig. 1b). Conversely, overexpression of GRK6 increased engulfment by NIH3T3 cells (Fig. 1c). These results demonstrated that GRK6 enhanced the clearance of apoptotic cells. In contrast to GRK6, GRK2 (K220R) expression increased apoptotic engulfment (Fig. 1a). However, GRK2 knockdown by siRNA resulted in significantly decreased engulfment, and overexpression of GRK2 greatly increased engulfment (Supplementary Fig. S1). These results indicated that GRK2 could enhance engulfment independent of its kinase activity, which is similar to the role of GRK2 in cell migration²⁰.

Next, we examined if GRK6 mediated apoptotic cell engulfment by macrophages. Bone marrow-derived macrophages (BMDMs) from wild-type (WT) mice expressed GRK6 (Supplementary Fig. S2) and efficiently engulfed apoptotic thymocytes. In comparison, BMDMs from GRK6-deficient mice had a significantly decreased ability to engulf apoptotic cells (Fig. 1d). GRK6-deficient BMDMs also had decreased uptake of fluorescent microspheres, although the extent of this decrease was less than that observed for apoptotic cell engulfment (Supplementary Fig. S3).

We further examined the contribution of GRK6 to apoptotic cell clearance by macrophages *in vivo*. Fluorescently labelled apoptotic thymocytes were injected into WT and GRK6-deficient mice. Phagocytosis by splenic macrophages from GRK6-deficient mice was approximately one-third less than that by macrophages from WT mice, which indicated that engulfment was impaired in GRK6-deficient splenic macrophages (Fig. 1e). Collectively, GRK6 contributes to the efficient engulfment of apoptotic cells in various types of phagocytes, including macrophages.

GRK6 operates upstream of Rac1 for engulfment. To determine the molecular mechanisms by which GRK6 enhances apoptotic engulfment, we examined whether Rac1 participated in the GRK6-mediated engulfment pathway. Rac1 is an indispensable molecule for apoptotic cell engulfment³. Consistent with the results of a previous study²¹, a DN Rac1 mutant, Rac1 (T17N), almost completely inhibited engulfment by NIH3T3 cells. WT Rac1 expression markedly enhanced engulfment, which confirmed Rac1's indispensable role in engulfment (Fig. 2a). Next, we co-expressed WT GRK6 and DN Rac1, Rac1 (T17N). Rac1 (T17N) expression completely abolished the enhanced

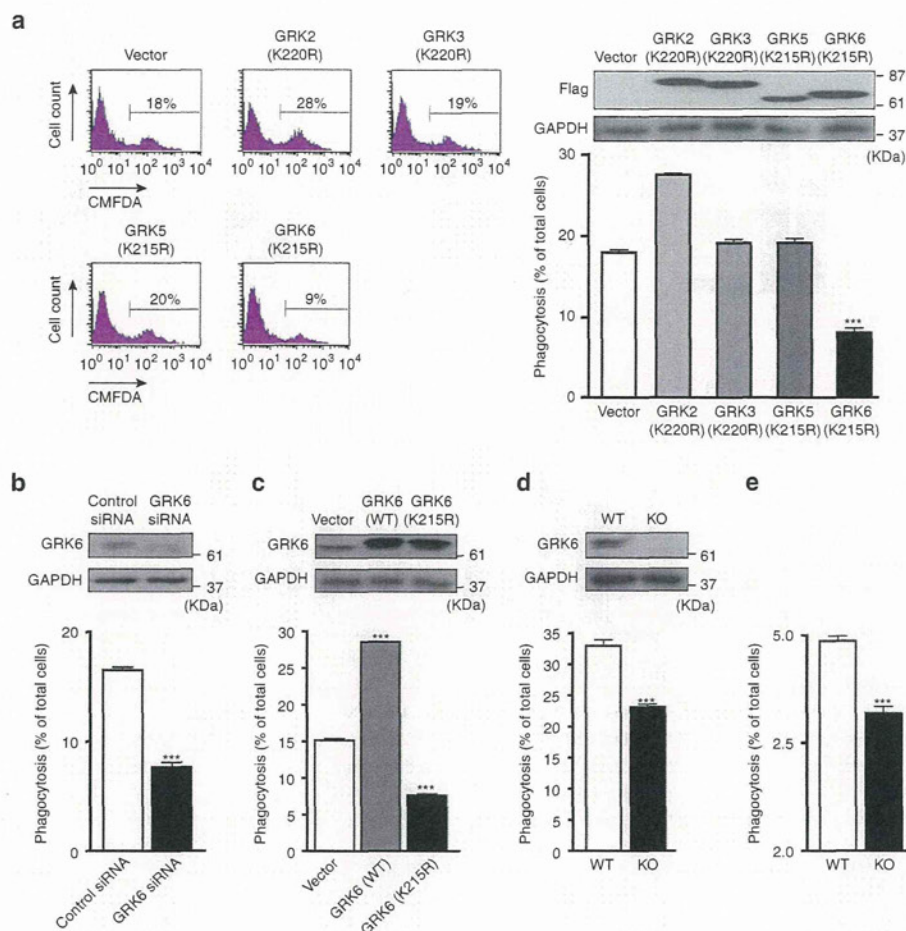


Figure 1 | Involvement of GRK6 in the engulfment of apoptotic cells. (a) NIH3T3 cells were infected with the empty retrovirus vector or the virus carrying the cDNA for kinase-inactive form of GRK2, GRK3, GRK5 or GRK6 (GRK2 (K220R), GRK3 (K220R), GRK5 (K215R) or GRK6 (K215R)) with N-terminal Flag tag. The infected cells (4×10^4 cells) were co-cultured with CMFDA-labelled WT thymocytes (1×10^6 cells) at 37 °C for 90 min. Percentages of the phagocytes carrying the engulfed thymocytes were determined by FACS as detailed in Methods. The representative FACS profiles with the NIH3T3 cells expressing GRK2 (K220R), GRK3 (K220R), GRK5 (K215R) or GRK6 (K215R) are shown from four independent experiments performed in triplicate. The expression level of each GRK mutant in NIH3T3 cells was determined by immunoblot analysis using anti-Flag and anti-GAPDH antibodies. (b) The engulfment ability of NIH3T3 cells transfected with control or GRK6 siRNA was estimated by FACS analysis as described in a. The cell lysates of the NIH3T3 cells were analysed by western blot with antibody against GRK6 or GAPDH. Expression level of GRK6 was decreased to about 30% of the normal level following treatment with GRK6 siRNA. (c) The engulfment ability of NIH3T3 cells expressing GRK6 (WT) or GRK6 (K215R) was evaluated by FACS as described in a. The level of GRK6 (WT) or GRK6 (K215R) was more than 10-fold greater than endogenous levels, determined by immunoblot using anti-GRK6 antibody. (d) BMDMs (1×10^5 cells) from WT and GRK6-deficient mice were co-cultured with CMFDA-labelled apoptotic thymocytes (1×10^6 cells) at 37 °C for 60 min. The percentage of the phagocytes carrying the engulfed thymocytes is presented. BMDM lysates from WT and GRK6-deficient mice were analysed by western blot with antibody against GRK6 or GAPDH. (e) CMFDA-labelled apoptotic thymocytes (8×10^7 cells) were injected to WT and GRK6-deficient mice from tail vein. Two hours after the injection, their spleens were isolated and stained with anti-CD11b antibody. Percentage of CD11b⁺ splenic macrophage carrying the labelled thymocytes was evaluated by flow cytometer. All the experiments were done at least three times; all graphs show average with s.e.m. *** $P < 0.001$. KO, knockout.

engulfment induced by GRK6 (Fig. 2a). In contrast, GRK6 (K215R) expression did not significantly affect Rac1-promoted engulfment (Fig. 2b). The formation of lamellipodia that is characteristic for Rac1 activation²² was observed in GRK6-expressing cells, whereas GRK6 (K215R) and Rac1 (T17N) expression significantly attenuated the formation of lamellipodia (Supplementary Fig. S4). These morphological results together with our other data regarding engulfment suggested that GRK6 activated Rac1. We next examined the effect of GRK6 on Rac1 activity using a pull-down assay with the Rac1-binding domain of PAK (PAK-RBD), which specifically binds to the GTP form of Rac1. As shown in Fig. 2c, this pull-down assay showed that

GRK6 overexpression significantly increased the level of Rac1-GTP, whereas the expression of GRK6 (K215R) decreased it. These results indicated that GRK6 enhanced engulfment through Rac1 activation.

GRK6 is part of a novel engulfment pathway. The best-known and best-established intracellular molecular pathways involved in engulfment are the DOCK180/ELMO/Rac1 and GULP/Rac1 pathways, which have been identified in *Caenorhabditis elegans* and are conserved in mammals. These pathways supposedly operate in parallel, although in a partially redundant manner⁵.

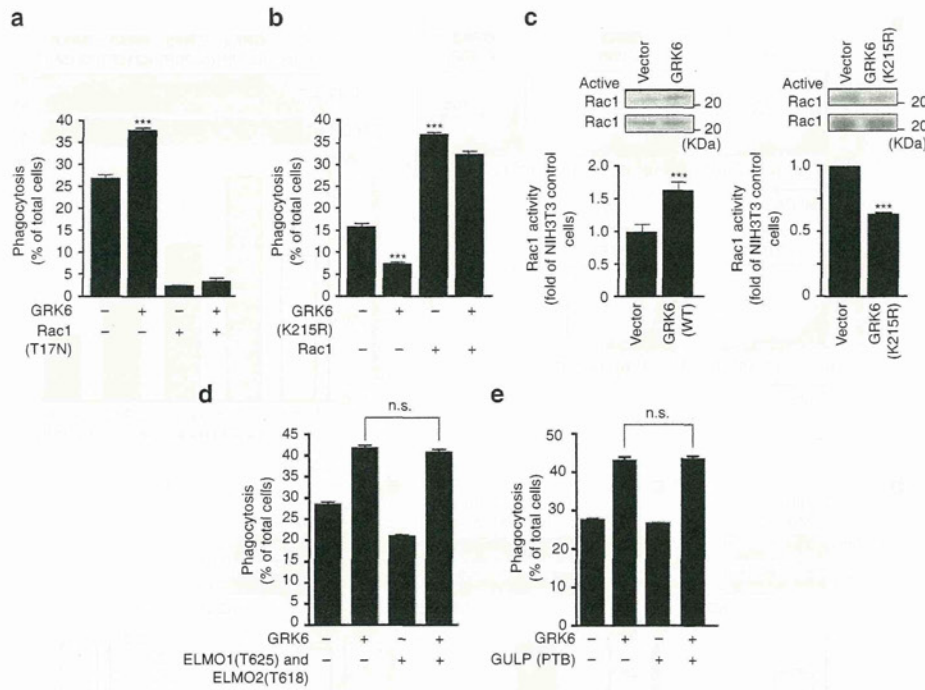


Figure 2 | GRK6 regulates engulfment of apoptotic cells via Rac1. (a,b) NIH3T3 cells were infected with retroviruses encoding WT GRK6 and DN Rac1 (T17N) (a), or kinase-inactive GRK6 (K215R) and WT Rac1 (b), either alone or in combination. The infected cells were subjected to the engulfment assay with CMFDA-labelled WT thymocytes. Percentages of the phagocytes carrying the engulfed thymocytes were determined by FACS. (c) NIH3T3 cells infected with the empty retrovirus vector or the virus carrying the cDNA for WT GRK6 were subjected to GTP-Rac1 pull-down assay using GST-CRIB. The pull-down samples were subjected to western blot using anti-Rac1 antibody and the level of GTP-bound Rac1 was quantified by densitometry, normalized against the total amount of Rac1 in the cell lysates. Data represent means \pm s.e.m. (error bars), $n=3$. (left panel) (d,e) NIH3T3 cells were infected with retroviral combinations of WT GRK6 and two DN forms of ELMO, ELMO1 (T625) and ELMO2 (T615) (d), retroviral combinations of WT GRK6 and a DN form of GULP, GULP (PTB), as indicated (e). The retrovirus-infected NIH3T3 cells were subjected to the engulfment assay. Percentages of the phagocytes carrying the engulfed thymocytes were determined by FACS. All the phagocytosis experiments were done at least three times, and the average numbers are shown with s.e.m. n.s., not significant. $***P<0.001$.

Thus, we examined if the GRK6-mediated engulfment pathway was related to these two signalling pathways. We generated DN ELMO mutants, ELMO1 and ELMO2, by truncating their C-terminal regions²³ and a DN GULP mutant by eliminating the phosphotyrosine-binding domain of GULP²⁴ and co-transfected these with GRK6. The expressions of both the ELMO mutants (Fig. 2d) and the GULP mutant (Fig. 2e) did not affect GRK6-mediated enhancement of apoptotic cell engulfment. These results suggested that the GRK6-mediated engulfment pathway was largely independent of two known pathways.

GIT1 enhances GRK6-mediated engulfment. To search for molecules that could be involved in GRK6-mediated Rac1 activation, we focused on the GRK-interacting ADP ribosylation factor GTPase-activating protein1 (GIT1). GIT1 is one of the few non-receptor proteins that interact with GRK6²⁵. However, a functional relationship between GRK6 and GIT1 and the binding region of GIT1 required for this interaction have not been established. GIT1 is expressed in various types of tissues and cells¹⁶. We confirmed that GIT1 was expressed in NIH3T3 cells, BMDMs and splenic macrophages (Supplementary Fig. S5a). Furthermore, GRK6 deficiency did not affect GIT1 expression in BMDMs (Supplementary Fig. S5b). GIT1 expression alone slightly increased the engulfment of apoptotic cells by NIH3T3 cells (Fig. 3a). However, when GIT1 was co-expressed with GRK6, GIT1 enhanced GRK6-mediated engulfment (Fig. 3a). To identify the amino-acid residues or region of GIT1 that were responsible

for GRK6-mediated engulfment, we made some point²⁶ and deletion²⁷ mutants of GIT1, as shown in Fig. 3b and Supplementary Fig. S6a. GIT1 (R39K) expression, which lacks the ADP ribosylation factor-GTPase-activator protein activity, had no effect on the GRK6-mediated engulfment (Supplementary Fig. S6b). In comparison, mutants that lacked the coiled-coil domain of GIT1, GIT1(Δ C) and GIT1(Δ AC) significantly attenuated the GRK6-mediated engulfment (Fig. 3a). These GIT1 mutants also inhibited the Rac1 activation by GRK6 (Fig. 3c). Immunoprecipitation experiments revealed that GRK6 interacted with GIT1 (Fig. 3d,e) independently of its kinase activity (Fig. 3f), although GRK6 directly phosphorylated GIT1 (Supplementary Fig. S7). Because the coiled-coil domain-deleted GIT1 mutants did not immunoprecipitate with GRK6, the coiled-coil domain was important for its interaction with GRK6 (Fig. 3d). This GRK6/GIT1 complex did not affect the GIT1-regulated signalling pathways that were previously reported²⁰ (Supplementary Fig. S8).

Radixin and moesin contribute to GRK6-mediated signalling. To further characterize the GRK6-mediated pathway for apoptotic engulfment, we employed a newly developed phosphoproteomic approach to identify target proteins for GRK6²⁸. We prepared three phosphoprotein-enriched fractions from vector-infected, GRK6 (WT)-infected and GRK6 (K215R)-infected NIH3T3 cells. The lysate proteins were labelled with one of the three different fluorescent probes: Vector: Cy2 (shown as blue pseudocolor), GRK6: Cy3 (shown as red pseudocolor) and

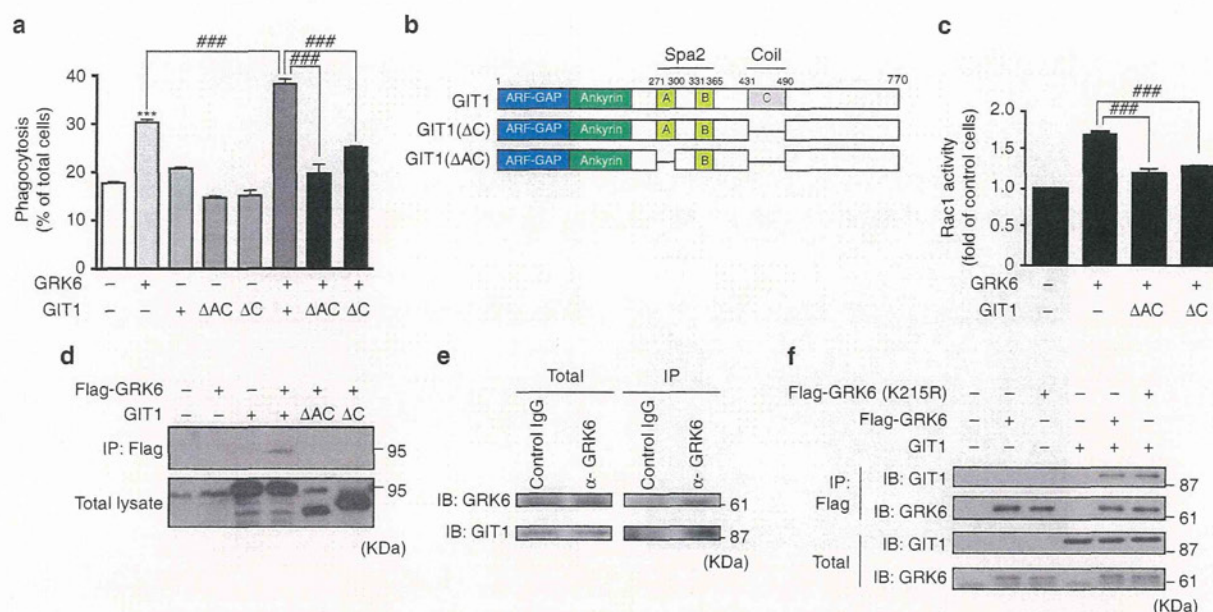


Figure 3 | GIT1 is involved in GRK6-mediated apoptotic engulfment. (a) NIH3T3 cells (4×10^4 cells) infected with the indicated retroviruses were co-cultured at 37 °C for 90 min with 1×10^6 cells CMFDA-labelled WT thymocytes. Percentages of the phagocytes carrying the engulfed thymocytes were determined by FACS. The experiments were done at least three times, and the average numbers are shown with s.e.m. (b) Schematic representation of GIT1 and its deletion mutants, GIT1 (Δ C) and GIT1 (Δ AC), used in this study. The numbers indicate the positions of the amino acids. (c) The activation state of Rac1 in NIH3T3 cells infected with the indicated retroviruses was measured in GTP-Rac1 pull-down assays with GST-CRIB. Data represent means \pm s.e.m. (error bars) of four independent experiments. (d) HEK293 cell lysates transiently transfected with the indicated plasmids were immunoprecipitated with anti-Flag antibody. Western blot was performed with anti-GIT1 antibody. (e) Cell extracts of BMDM from WT mice were immunoprecipitated with normal rabbit IgG or anti-GRK6 antibody. The total lysates and immunoprecipitates (IPs) of BMDMs were immunoblotted (IB) with anti-GRK6 and anti-GIT1 antibodies. (f) NIH3T3 cell lysates infected with the indicated retroviruses were immunoprecipitated with anti-Flag antibody. The IPs were subjected to western blot analysis with anti-GRK6 and anti-GIT1 antibodies. All the immunoprecipitation experiments were done at least three times, and representative data are shown. *** $P < 0.001$, ### $P < 0.001$.

GRK6 (K215R): Cy5 (shown as green pseudocolor). The labelled proteins in each lysate were mixed together, and the mixture was subjected to two-dimensional difference gel electrophoresis (2D-DIGE) followed by fluorescence scanning (Fig. 4a). A small proportion of spots showed a GRK6-induced increase in their acidic forms. We picked out several of these red spots and analysed their protein sequences by mass spectrometry (MS) combined with liquid chromatography. This showed that these proteins were radixin and moesin (Fig. 4b), both of which belong to the same protein ezrin/radixin/moesin (ERM) family. These proteins are known to link integral membrane proteins to the cortical actin cytoskeleton located beneath the plasma membrane, thereby contributing to cytoskeletal remodelling¹⁷ and engulfment²⁹. Phosphorylation at a carboxy-terminal threonine residue (Thr567 of ezrin, Thr564 of radixin and Thr558 of moesin) has been implicated in the function of ERM family proteins^{30,31}. Therefore, we first examined whether phosphorylation at these sites was induced by the GRK6 overexpression in NIH3T3 cells. Western blotting using an anti-phosphorylated ERM antibody showed that radixin and moesin phosphorylation was increased in NIH3T3 cells due to GRK6 expression (Fig. 4c). This specific phosphorylation was also examined by 2D-western blotting. In this detection system, chemiluminescent signals from the anti-ERM antibody or the phospho-ERM antibody were simultaneously detected with the fluorescent probes used for protein labelling of the lysate mixtures of NIH3T3 cells that expressed WT GRK6 (labelled with Cy3) and GRK6 (K215R) (labelled with Cy5) (Supplementary Fig. S9). Accordingly, we could confirm that these spots had shifted to the more acidic side

of the membrane due to GRK6 overexpression and corresponded to phosphorylated ERMs.

We next compared the amounts of the phosphorylated forms of ERMs in BMDMs prepared from WT and GRK6-deficient mice. This revealed that phosphorylated moesin, which is the most abundant and main ERM protein in BMDMs, was significantly decreased in GRK6-deficient BMDMs, which indicated that GRK6 was involved in moesin phosphorylation at its carboxy terminus *in vivo* (Fig. 4d). However, GRK6 did not directly phosphorylate radixin and moesin (Supplementary Fig. S10). ERM phosphorylation by GRK6 was significantly attenuated by the expression of GIT1 mutants that lacked the coiled-coil domain, which suggested that ERM phosphorylation was dependent on the GRK6/GIT1 complex (Fig. 4e). In comparison, GRK6-induced ERM phosphorylation was not affected by Y27632, U0126 and LY294002 (Supplementary Fig. S11), which suggested that Rho-kinase, MEK/ERK and phosphatidylinositol-3-kinase were not involved in ERM phosphorylation. When siRNAs for radixin or moesin were transfected into GRK6-overexpressing NIH3T3 cells, engulfment by these cells was markedly attenuated without affecting the GRK6 expression level (Fig. 4f, Supplementary Fig. S12). These results suggest that radixin and moesin phosphorylation contributes to the GRK6-mediated signalling pathway.

GRK6-deficient mice exhibit an autoimmune-like disease. An *in vivo* defect in apoptotic cell removal reportedly caused the development of an autoimmune disease that resembled human SLE³². Thus, we examined whether GRK6-deficient mice

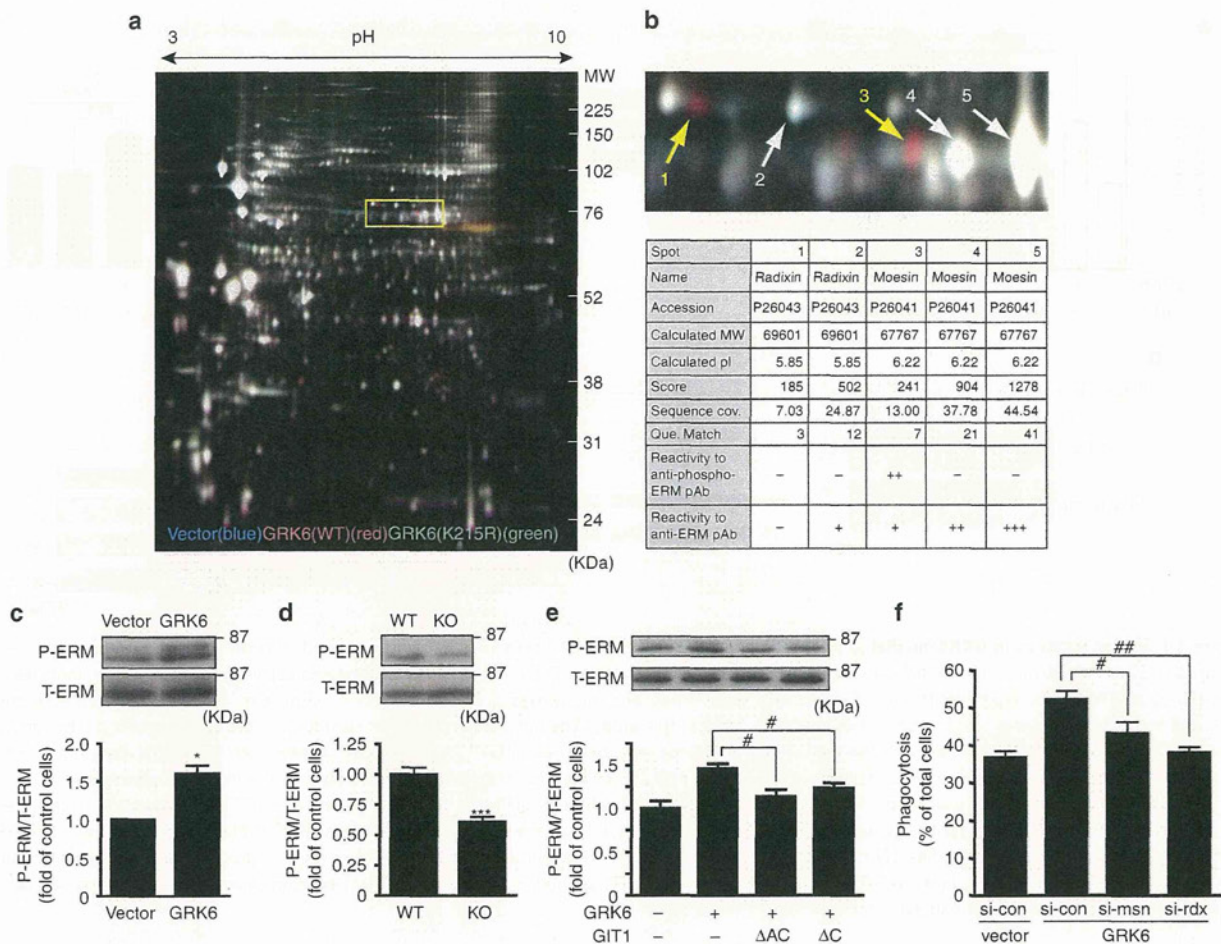


Figure 4 | Radixin and moesin phosphorylation is induced by GRK6. (a) A representative gel image of 2D-DIGE of phosphoprotein fractions from NIH3T3 cells infected with the empty retrovirus vector (Cy2-labelled, blue), the virus carrying the cDNA for WT GRK6 (Cy3-labelled, red) or GRK6 (K215R) (Cy5-labelled, green). (b) Zoom-in view of an area in a representing GRK6 (WT)-induced (yellow arrow, red spot) and unchanged (white arrow, white spot) protein spots. The table summarizes the protein identity, accession number, calculated molecular weight, calculated pI, Mascot score, sequence coverage, query match and reactivity to anti-phospho-ERM antibody that specifically recognizes Thr567 of ezrin, Thr564 of radixin and Thr558 of moesin and anti-ERM antibody for the numbered spots. (c) NIH3T3 cells are retrovirally transfected with GRK6. The cell lysates were subjected to immunoblotting with the anti-phospho-ERM antibody or anti-ERM antibody. Data represent means \pm s.e.m. (error bars). (d) The cell lysates prepared from BMDMs of WT and GRK6-deficient mice were immunoblotted with the indicated antibodies. Data represent means \pm s.e.m. (error bars). (e) Cell lysates of NIH3T3 cells infected with the indicated retroviruses were subjected to western blot analysis using anti-phospho-ERM antibody or anti-ERM antibody. (f) GRK6 was transfected with siRNA for control, radixin (rdx) or moesin (msn) and subjected to the engulfment assay. All the experiments were done at least three times, and representative data are shown. * $P < 0.05$, *** $P < 0.001$, # $P < 0.05$ and ## $P < 0.01$. KO, knockout; MW, molecular weight; P-ERM, phospho-ERM; T-ERM, total-ERM.

developed autoimmunity. An increase in the amount of anti-dsDNA in serum is one of the most important and reliable criteria for SLE. We first evaluated levels of anti-dsDNA in sera collected from 40-week-old GRK6-deficient and WT mice. Increased anti-dsDNA antibody levels were detected in GRK6-deficient mice (Fig. 5a). A major pathogenic consequence of autoantibody production is the deposition of immune complexes in the kidney, which leads to glomerulonephritis. Immunohistochemical analysis of kidney sections showed that there was significantly increased IgG deposition in aged GRK6-deficient mice (Fig. 5b). Consistent with IgG deposition, mesangial expansion, which reflects glomerulonephritis, was also observed in the kidneys of GRK6-deficient mice (Fig. 5c). In addition, GRK6-deficient mice developed age-dependent splenomegaly that was associated with increased numbers of splenocytes (Fig. 5d,e). At 40 weeks of age, their spleens were approximately 1.6-fold

heavier than WT mouse spleens. The white pulp in the spleen was enlarged in GRK6-deficient mice (Supplementary Fig. S13), as was observed in MFG-E8-deficient mice that developed lupus-like autoimmune disease due to the impaired uptake of apoptotic cells³³. We also examined changes in the lymphoid and myeloid cell populations in the spleens of 40-week-old GRK6-deficient mice. The ratios of B cells to T cells and the frequencies of CD11c⁺, CD11b⁺ cells and regulatory T cells were similar in WT and GRK6-deficient mice (Supplementary Fig. S14a–c). Double staining with anti-CD19 and anti-CD69 antibodies was also similar in GRK6-deficient and WT mice, which indicated that the splenomegaly in GRK6-deficient mice was not due to aberrant B-cell activation (Supplementary Fig. S14d). However, the ratio of CD4/CD8 T cells increased in GRK6-deficient mice with a decrease in the CD8 T-cell population, similar to MFG-E8-deficient mice³⁴ (Supplementary Fig. S15a). Therefore,

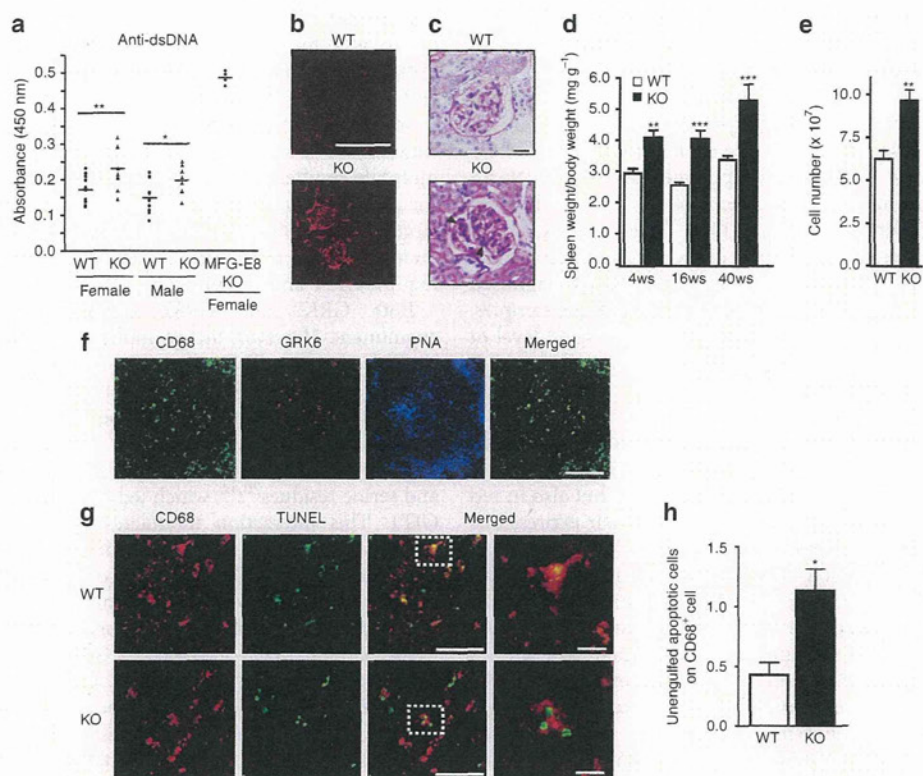


Figure 5 | GRK6-deficient mice spontaneously develop autoimmune disease. (a) Serum from 40-week-old control WT and GRK6-deficient female (WT: $n = 14$, GRK6-deficient: $n = 9$) and male mice (WT: $n = 12$, GRK6-deficient: $n = 8$) were collected and tested for presence of anti-dsDNA antibodies. Serum from 40-week-old MFG-E8-deficient female mice ($n = 4$) was used as a positive control. (b) Increased deposition of immune complexes in glomeruli of GRK6-deficient mice at 40 weeks of age was assessed by anti-immunoglobulin staining. Scale bar, 100 μm . (c) Paraffin-embedded kidney sections of WT and GRK6-deficient mice at 40 weeks of age were stained using periodic acid-Schiff. Arrowheads indicate a mesangial expansion with increase in matrix and cellularity owing to increased mononuclear cells. Scale bar, 20 μm . (d) Spleens isolated from WT and GRK6-deficient mice of 4-week-old ($n = 8$), 16-week-old ($n = 4$) and 40-week-old ($n = 9$) were weighed, and spleen weight relative to body weight were measured. And the average numbers are shown with s.d. (e) Splenocytes from WT ($n = 7$) and GRK6-deficient mice ($n = 6$) of 40-week-old mice were counted, and the numbers were shown in the graph. (f) Spleen sections from WT mice were stained with anti-CD68 (green), anti-GRK6 (red) and PNA (blue). The fourth column represents the two-colour (anti-CD68 and anti-GRK6) overlay image. Scale bar, 100 μm . (g) Spleen sections from 40-week-old WT and GRK6-deficient mice were double-stained with TUNEL (green) and anti-CD68 antibody (red). Staining profiles were merged in the third column. Scale bar, 50 μm . Enlarged images are shown in the fourth column. Scale bar, 10 μm . (h) The numbers of unengulfed cells associated with CD68-positive macrophages were counted for 40-80 macrophages and are presented as the number per macrophages. The average numbers are shown with s.e.m. All immunohistochemical data are representative of four independent experiments. * $P < 0.05$, ** $P < 0.01$ and *** $P < 0.001$. KO, knockout.

these results support the hypothesis that GRK6-deficient mice developed an autoimmune phenotype, though the symptoms were mild. We also found differences in the CD8^+ T-cell populations that mainly affect lupus³⁴ (Supplementary Fig. S15b). Naive T cells (CD44^{lo} and CD62L^{hi}) were decreased in GRK6-deficient mice, whereas memory T cells (CD44^{hi}) were increased in these mice. CD8^+ memory T-cell populations characterized by CD44 expression can be subdivided into effector (low levels of CD62L) and central memory T cells (high levels of CD62L)³⁵. In GRK6-deficient mice, the ratio of $\text{CD62L}^{\text{lo}}/\text{CD62L}^{\text{hi}}$ cells among the CD8^+ memory T-cell population was increased, which indicated that effector memory T cells had increased reminiscent of aged MFG-E8-deficient mice³⁴ (Supplementary Fig. S15b). These results suggested that CD8^+ T-cell activation was induced by the increased presentation of apoptotic cell-associated antigens by splenic antigen-presenting cells. In young GRK6-deficient mice at 8 weeks of age, no significant abnormalities were found in their spleen cell subsets (Supplementary Fig. S16).

GRK6 is involved in apoptotic cell clearance by macrophages. Macrophages in the germinal centre of the spleen are involved in

removing apoptotic B cells. Inefficient engulfment by macrophages supposedly triggers immune responses, which results in SLE-like autoimmunity in mice^{33,36,37}. Because we had detected autoimmune properties and abnormalities of the spleen in GRK6-deficient mice, we examined whether GRK6 was expressed by germinal centre macrophages, which were characterized by their CD68 expression. Immunohistochemical staining revealed that GRK6 was expressed in CD68^+ macrophages in the germinal centre (Fig. 5f). TdT-mediated dUTP nick end labeling (TUNEL)-stained apoptotic cells were also observed in this area (Fig. 5g). Furthermore, more TUNEL-positive cells were associated with CD68^+ macrophages in GRK6-deficient mice, which indicated that many undigested apoptotic cells were present in the spleens of GRK6-deficient mice (Fig. 5h). The numbers of CD68^+ macrophages in the white spleen pulp of GRK6-deficient mice were the same as in WT mice, indicating that GRK6 did not affect the development of these macrophages (Supplementary Fig. S17). GRK6 was not involved in the cells' growth, differentiation or apoptosis (Supplementary Fig. S18). Therefore, GRK6 has an important role in the removal of apoptotic B cells by macrophages in the germinal centre without affecting the development,

cell growth, differentiation or apoptosis of these macrophages.

We next examined whether the GRK6 expression level was linked to autoimmune diseases. The MRL/*lpr* mouse is a well-known mouse model of SLE. Immunohistochemical analysis of the spleens from MRL/*lpr* mice revealed that the GRK6 expression levels in many splenic macrophages of these mice were markedly increased (Supplementary Fig. S19a,b), which was accompanied with an increase in the numbers of macrophages (Supplementary Fig. S19c). Then, we examined whether GRK6 expression was altered in the macrophages of SLE patients. Among 1,528 autopsies, we could find 6 cases diagnosed with SLE, which is a relatively rare disease. Among these samples, we found an autopsied spleen that had a high expression level of GRK6 in inflammatory cells compared with that of non-SLE patients (Supplementary Fig. S19d).

GRK6 regulates engulfment of senescent red blood cells.

Immunohistochemical analysis showed that GRK6 was expressed not only in CD68⁺ macrophages in the white pulp but also in red pulp macrophages, which was characterized by their expressions of F4/80⁺ (Fig. 6a). Red pulp macrophages have a role in removing senescent red blood cells, thereby contributing to iron recycling in the body. Dead red blood cells express phosphatidylserine, and their clearance is mediated by phosphatidylserine recognition^{38,39}. Thus, we examined the involvement of GRK6 in the removal of senescent red blood cells, a defect of which leads to iron deposition in the red pulp⁴⁰. Splenic red macrophages isolated from GRK6-deficient mice exhibited a defect in their ability to take up dead red blood cells *in vitro* (Fig. 6b). We also examined the phagocytosis of red blood cells by splenic red pulp macrophages *in vivo*. Fluorescently labelled dead red blood cells were injected into WT or GRK6-deficient mice. At 24 h after this injection, splenic macrophages were collected and their engulfment capability was analysed. This showed that the engulfment of dead red blood cells by red pulp macrophages was attenuated in GRK6-deficient mice (Fig. 6c). Perl's Prussian staining, which specifically stains iron, revealed that there was increased iron accumulation in the spleen red pulp of GRK6-deficient mice (Fig. 6d). Quantitative determinations of the iron contents in spleens also showed that splenic iron concentrations were increased in GRK6-deficient mice (Fig. 6e). However, the numbers of red pulp splenic macrophages were not decreased in GRK6-deficient mice (Fig. 6f), which indicated that iron deposition was not due to the abnormal development of splenic red pulp macrophages. Expression levels of ferroportin-1, a major iron exporter and hepcidin, an inhibitor of ferroportin-1, were the same in the spleens and livers of WT and GRK6-deficient mice (Fig. 6g, Supplementary Fig. S20). This suggested that iron export was normal in splenic macrophages of GRK6-deficient mice. In addition, GRK6-deficient mice did not exhibit any abnormal red pulp macrophage populations^{41,42} in their spleens (Supplementary Fig. S21). These results suggested that iron deposition in GRK6-deficient mice was caused by inefficient erythrophagocytosis. However, serum iron parameters and the life spans of red blood cells were normal in GRK6-deficient mice (Supplementary Tables 1 and 2 and Supplementary Fig. S22).

We finally compared iron deposition in the spleens of GRK6-deficient mice with that in WT mice after acute anaemia. Acute haemolysis induced by injecting phenylhydrazine is accompanied by shrinkage of the white pulp and causes an enlargement of the red pulp due to an influx of dead red blood cells⁴³ (Supplementary Fig. S23a). More iron was deposited in the spleens of GRK6-deficient mice after phenylhydrazine injection (Supplementary Fig. S23b). Similar results were obtained after inducing acute anaemia by phlebotomy (Supplementary Fig. S23c).

Discussion

GRK6 is a member of the GRK family of proteins that were initially identified as kinases responsible for the desensitization and downregulation of GPCRs. In this report, we identified GRK6 as an important molecule that promotes efficient apoptotic cell engulfment by several types of macrophages. A deficiency of this molecule resulted in an autoimmune-like disease and splenic iron accumulation in these mice. GRK6-mediated engulfment was largely independent of two well-established intracellular engulfment pathways, DOCK180/ELMO/Rac1 and GULP/Rac1, but did require GIT1 and the phosphorylation of radixin and moesin.

Both GRK2 and GRK6 expressions enhanced apoptotic engulfment. However, the promotion of apoptotic cell engulfment by GRK6 but not GRK2 depends on its kinase activity. A previous report showed that GRK2 positively regulated integrin-dependent epithelial cell migration in a kinase activity-independent manner, which was orchestrated by GIT1²⁰. The function of GRK2 in cell migration was regulated by its phosphorylation at certain tyrosine and serine residues^{20,44}, which led to the interaction of GRK2 with GIT1. This interaction modulates the Rac1/PAK/MEK/ERK1/2 pathway in response to sphingosine-1-phosphate and adhesion²⁰. In contrast, the GRK6-GIT1 complex did not significantly influence this pathway (Supplementary Fig. S8). Considering these differences, the pro-migratory or pro-engulfmental signal transduction pathway mediated by GRK2^{44,45} or GRK6 is regulated by distinct molecular mechanisms, although GIT1 is common to both the pathways. GRK2 was reported to directly phosphorylate ERM⁴⁶, whereas it did not undergo direct phosphorylation by GRK6. This may also contribute to the different signalling pathways by the two GRKs. The molecular mechanism by which GRK2 or GRK6 defines its specific signal transduction pathway will be an interesting theme for future studies.

With regard to the clearance of senescent red blood cells by splenic macrophages, the CD47-SHPS-1 regulatory system has been well studied⁴⁷. The CD47-SHPS-1 system defines self- and non-self recognition by macrophages, which generates the so-called 'Don't eat me signal' that enables viable red blood cells to escape engulfment by phagocytes. In this study, we found that GRK6 promoted the engulfment of senescent red blood cells by red splenic macrophages and contributed to iron homeostasis. A recent report⁴⁰ showed that Spic-deficient mice selectively lost splenic red pulp macrophages. In these mice, iron deposition in their spleens was observed due to the inefficient engulfment of dead red blood cells. In spite of this iron deposition, Spic-deficient mice did not show any significant abnormalities in total iron homeostasis, which was similar to GRK6-deficient mice. To date, studies on the diseases of iron metabolism have usually focused on the proteins that directly alter iron transport, such as iron transporters/exporters, receptors for iron-binding proteins or the regulators of the activities of these transporters and receptors. Our study provides a new model of human iron disorders in the spleen. GRK6 may be a candidate gene that is responsible for iron overload in some patients.

In summary, we revealed that GRK6 was involved in apoptotic cell clearance by two independent subsets of macrophages in the spleen. GRK6 greatly contributed to removing unnecessary B cells by splenic white pulp macrophages and removing senescent red blood cells by splenic red pulp macrophages. However, we cannot rule out the possibility that some unidentified roles for GRK6, other than engulfment, influence the phenotypes of GRK6-deficient mice, as our experiments were performed using GRK6 systemic knockout mice. Thus, to conclude that the phenotypes observed here were due to engulfment defects by GRK6-deficient macrophages, it will be necessary to examine the phenotypes of GRK6-deficient mice after transplanting bone marrow cells from WT mice and vice versa.

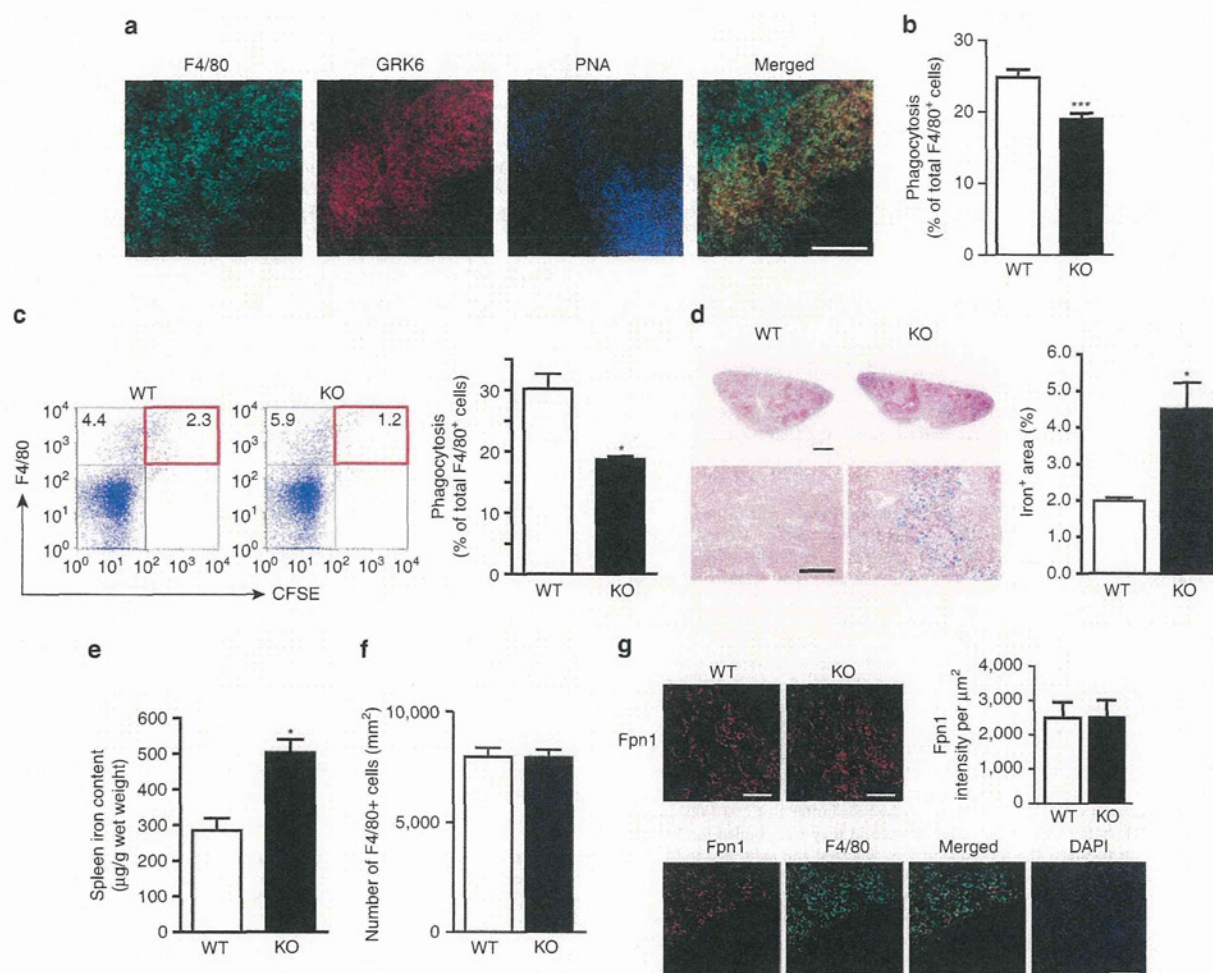


Figure 6 | GRK6-deficient mice manifest iron accumulation in splenic red pulp. (a) Spleen sections from WT mice were stained with anti-F4/80 antibody (green), anti-GRK6 antibody (red) and peanut agglutinin (PNA) (blue). The fourth column is the merged image of F4/80 and GRK6. Scale bar, 100 μm . (b) Splenic cells from WT and GRK6-deficient mice (1×10^6 per well) were co-cultured with CMFDA-labelled apoptotic red blood cells (4×10^7 /well) for 90 min at 37 $^{\circ}\text{C}$. Percentage of F4/80-positive cells carrying the engulfed red blood cells was determined by FACS analysis and shown in the graph. Error bars represent the mean \pm s.e.m. $n = 4$. (c) Carboxyfluorescein diacetate succinimidyl ester (CFSE)-labelled apoptotic red blood cells were injected to WT and GRK6-deficient mice from tail vein. Percentage of F4/80 $^{+}$ splenic macrophage carrying the labelled red blood cells was evaluated by FACS. All numbers within FACS profiles correspond to the percentage of cells within each region. Error bars represent the mean \pm s.e.m. $n = 3$. (d) Spleen sections from 16-week-old WT and GRK6-deficient mice were stained with Perl's Prussian blue to visualize the iron deposits. Scale bar, 300 μm . Enlarged images are shown in the lower column. Scale bar, 100 μm . Areas positive for iron staining were quantified and showed as a percentage of the total surface area of the field. The average numbers are shown with s.d. $n = 3$. (e) Iron levels of spleens from 16-week-old WT and GRK6-deficient mice on a standard diet were determined. Error bars represent the mean \pm s.e.m. $n = 5$. (f) The numbers of F4/80 $^{+}$ macrophages in the splenic red pulp were counted in WT and GRK6-deficient mice. The numbers (cells per mm^2) were determined by four different fields (0.045 mm^2) of spleen sections from WT and GRK6-deficient mice. Error bars represent the mean \pm s.e.m. $n = 3$. (g) Spleen sections from WT and GRK6-deficient mice were stained with anti-ferroportin-1 (Fpn1) antibody. Fpn1 signal intensity in red pulp areas was determined and showed in the graph. Error bars represent the mean \pm s.e.m. Representative images of Fpn1 (red) and F4/80 (green), the merged and 4',6-diamidino-2-phenylindole (DAPI) images are shown. $n = 4$. Scale bar, 50 μm . * $P < 0.05$ and *** $P < 0.001$. KO, knockout.

Methods

In vitro phagocytosis assay. For uptake assays *in vitro*, we used apoptotic thymocytes or red blood cells as preys. Thymocytes or red blood cells from 4- to 8-week-old C57BL/6 mice were isolated and labelled with 1 μM CMFDA (Life Technologies) by incubating them at 37 $^{\circ}\text{C}$ for 30 min. After the labelling, the thymocytes were allowed to undergo apoptosis by treating thymocytes with 10 μM dexamethasone for 4 h at 37 $^{\circ}\text{C}$. The labelled red blood cells were suspended in PBS and incubated in the incubator (5% CO_2 , 37 $^{\circ}\text{C}$) for 24 h to induce apoptosis. The labelled apoptotic thymocytes or apoptotic red blood cells were added on the NIH3T3 cells (4×10^4 cells) and BMDM (2×10^5 cells) or splenic macrophages (1×10^6 cells), respectively, in a 24-well plate and co-cultured at 37 $^{\circ}\text{C}$. The NIH3T3 cells, BMDM and splenic macrophages were vigorously washed by PBS, followed by the treatment with 0.2% trypsin containing 1 mM

EDTA. The detached cells were analysed by flow cytometry using a FACS Calibur (BD Biosciences).

GTP-Rac1 pull-down assay. Retrovirus-infected cells were lysed by GTP-Rac1 pull-down assay buffer (50 mM Tris-Cl (pH 7.5), 0.1% Triton X-100, 10% glycerol, 150 mM NaCl, 30 mM MgCl_2 , 1 mM DTT, 1 mM PMSF, 2 $\mu\text{g ml}^{-1}$ leupeptin and 10 μM pepstatin). The lysates were collected and centrifuged at 15,000 r.p.m. for 10 min at 4 $^{\circ}\text{C}$ to remove cell debris. An amount of 10 μg GST-PAK-Rac1/Cdc42 binding domain and 30 μl Glutathione-Sepharose beads were added to each lysate. The mixtures were incubated at 4 $^{\circ}\text{C}$ for 1 h with gentle rotation. After the incubation, they were subjected to a wash by using the pull-down assay buffer and a brief centrifuge (5,000 r.p.m. for 1 min). The wash was repeated twice and, finally,

the beads were boiled in 60 μ l SDS sample buffer for 5 min at 95 °C. After the centrifuge, the samples were analysed by western blotting using anti-Rac1 antibody (BD Transduction).

In vivo phagocytosis assay. For splenic macrophage uptake assays, we intravenously injected 8×10^7 CMFDA-labelled apoptotic thymocytes into 10- to 12-week-old WT or GRK6-deficient mice. Two hours after the injection, the mice were killed and their spleens were extirpated. The spleens were smashed between two glass slides, and single-cell splenocyte suspensions were stained with anti-CD11b-APC to identify macrophage population after lysis of red blood cells. Cells were analysed by flow cytometry.

Engulfment of red blood cells in vivo. Red blood cells isolated from WT mice were suspended in 30 ml PBS and incubated with 5 μ M carboxyfluorescein diacetate succinimidyl ester (Invitrogen) for 10 min at room temperature. After the incubation, the cells were washed three times by PBS and suspended in 2 ml PBS. The cell suspension of 200 μ l was injected into WT or GRK6-deficient mice. Twenty-four hours after the injection, spleens of the mice were isolated and minced. The isolated splenocytes were stained with anti-F4/80-APC and analysed by flow cytometry.

Immunoprecipitation. NIH3T3 cells or transfected HEK293 cells expressing Flag-GRK6 and HA-GIT1 were washed and scraped by lysis buffer 1 (50 mM HEPES (pH 7.5), 250 mM NaCl, 2 mM EDTA, 10% glycerol, 0.5% NP40, 1 mM Na₃VO₄ and 1 mM NaF) containing protease inhibitors (Nacalai). The scraped cells were incubated on ice for 30 min and centrifuged at 14,000 r.p.m. for 10 min at 4 °C. The supernatant was collected and rotated gently for 90 min at 4 °C after adding 20 μ l anti-Flag antibody beads (Sigma). In the experiment to detect the endogenous interaction between GRK6 and GIT1 in BMDM, the cells were lysed in lysis buffer 2 (50 mM Tris-Cl (pH 7.5), 300 mM NaCl, 0.1% SDS, 1% Triton X-100, 0.5% Sodium deoxycholate, 1 mM Na₃VO₄ and 1 mM NaF) containing protease inhibitors (Nacalai). The lysed cells were incubated on ice for 15 min and centrifuged at 14,000 r.p.m. for 10 min at 4 °C. The collected supernatant was then incubated with anti-GRK6 antibody (Santa Cruz Biotechnology) overnight at 4 °C, followed by the incubation with Protein A-Sepharose beads (GE Healthcare) for 2 h. After the incubation, the beads were washed three times by lysis buffer 1 or 2 of 1,000 μ l, and 20 μ l SDS sample buffer was added to the beads and they were boiled for 5 min at 95 °C. After centrifugation, the supernatant was collected and subjected to SDS gel electrophoresis and western blotting with antibodies (mouse anti-HA (1:2,000 dilution; Roche), rabbit anti-GIT1 (1:2,000 dilution; Santa Cruz Biotechnology), rabbit anti-GRK6 (1:4,000 dilution; Santa Cruz Biotechnology) and horseradish peroxidase-conjugated anti-mouse IgG (1:5,000 dilution; Santa Cruz Biotechnology) or anti-rabbit IgG (1:5,000 dilution; Santa Cruz Biotechnology).

Two-dimensional difference gel electrophoresis. Phosphoprotein-enriched fractions were subjected to 2D-DIGE essentially as described previously²⁸. Briefly, total cell lysates were prepared from NIH3T3 cells overexpressing vector alone, GRK6 or GRK6 (K215R). Then, phosphoproteins in each cell lysate were enriched by using the Phosphoprotein Purification Kit (Qiagen), and interfering nonprotein material was subsequently removed (2-D Clean-Up Kit; GE Healthcare). Thirty microgram of the resultant phosphoprotein-enriched fractions were minimally labelled with 400 pmol Cy2, Cy3 or Cy5 fluorescent dye (CyDye DIGE Fluors, GE Healthcare) for 30 min on ice. After quenching the labelling reaction with 10 nmol lysine, these differentially labelled samples were mixed and subjected to first-dimension isoelectric focusing on immobilized pH gradient strips (24 cm; pH 3–10 non-linear) using an Ettan IPGphor II system. The second-dimensional SDS-PAGE was carried out on 9% acrylamide gel. The Cy2, Cy3 and Cy5 signals were individually acquired with a Typhoon 9400 scanner (GE Healthcare).

Protein identification by MS. After obtaining fluorescent images, the 2D-DIGE gel was silver-stained (Thermo Fisher Scientific/Pierce). Protein spots were excised and digested with trypsin (Promega). The resultant peptides were analysed by a capillary liquid chromatography system (Waters/Micromass, Manchester, UK) connected to a Q-TOF2 mass spectrometer (Waters/Micromass). Raw data were acquired and processed using MassLynx version 4.0 (Waters/Micromass) to generate a peak list file for MS/MS ion search. The peak list files were searched against the NCBI non-redundant protein database restricted to *Mus musculus* using the MS/MS ion search on Mascot search engine (Matrix Science).

Immunohistochemistry. Cryosections (4 μ m) of the spleen of WT or GRK6-deficient mice were fixed in cold acetone for 10 min and blocked with PBS containing 3% BSA for 1 h. After the blocking, the slides were incubated with anti-GRK6 (1:50 dilution; Santa Cruz Biotechnology), anti-CD68 (1:200 dilution; Serotec), anti-F4/80 (1:200 dilution; Serotec) and PNA (1:50 dilution; Vectashield) overnight at 4 °C, followed by staining with fluorescent-conjugated secondary antibodies. For staining with an antibody against ferroportin-1, livers and spleens of mice were fixed with 4% paraformaldehyde (PFA) overnight at 4 °C and

embedded in FSC22 Frozen Section Media (Leica Microsystems). Tissue sections (6 μ m in thickness) were blocked with 3% BSA and reacted with anti-ferroportin-1 (1:200; Alpha Diagnostics) overnight at 4 °C. Then, the sections were incubated with AlexaFluor 594 goat anti-rabbit antibody (Invitrogen). TUNEL assays were performed according to the manufacturer's instructions (ApoTag Fluorescein Direct In Situ Apoptosis Detection Kit; Millipore). For detection of immune complex in the kidney, 40-week-old mouse kidneys were fixed with 4% PFA and embedded in OCT compound (Tissue-Tek). Kidney sections that were 4- μ m thick were blocked with PBS containing 3% BSA and stained with Cy3-conjugated F(ab')₂ of goat anti-mouse IgG (Jackson ImmunoResearch Laboratories). Perl's Prussian blue stain or hematoxylin and eosin stain was performed according to the manufacturer's protocol (Sigma) by using paraffin-embedded spleen sections fixed by 4% PFA. Kidney sections fixed with 4% PFA were subjected to periodic acid-Schiff stain according to the standard procedures. All the stained sections were observed under a fluorescence microscope (Keyence BZ-9000) or a confocal microscope (Olympus FV10i or Nikon A1Rsi).

Enzyme-linked immunosorbent assay. The serum from 40-week-old WT, GRK6-deficient and MFG-E8-deficient mice was diluted 25 times in PBS, and 100 μ l of the diluted serum was added on the 96-well enzyme-linked immunosorbent assay plates coated with double-stranded DNA (Mesacup DNA-II test; MBL). One hour after the incubation at room temperature, the serum was removed and the plates were incubated with horseradish peroxidase-conjugated goat antibody against anti-mouse Ig (G + M + A) (Cappel) for 1 h. The peroxidase activity was detected by the Peroxidase Detection Kit (Sumitomo), and the absorbance of 450 nm was measured by a microplate reader (Berthold Technologies).

Measurement of iron concentration in spleen. Spleens were weighed and digested in 10% trichloroacetic acid with homogenizer and incubated at 65 °C for 24 h with agitation. The solution was centrifuged at 14,000 r.p.m. for 5 min. The supernatant was collected and neutralized with NaOH to adjust pH > 2. The resultant solution was subjected to iron measurement by Mettaloassay LS-MPR Kit (AKJ Global Technology, Japan) based on Nitroso-PSAP method according to the manufacturer's protocol. The absorbance of 750 nm was determined by using a spectrometer.

Statistical analysis. The results are represented as means \pm s.e.m. from at least three independent experiments. We employed Student's *t*-test for comparisons for two groups and analysis of variance with the Student-Newman-Keuls test for multiple-group comparison.

References

- Peter, C., Wesselborg, S., Herrmann, M. & Lauber, K. Dangerous attraction: phagocyte recruitment and danger signals of apoptotic and necrotic cells. *Apoptosis* **15**, 1007–1028 (2010).
- Maderna, P. & Godson, C. Phagocytosis of apoptotic cells and the resolution of inflammation. *Biochim. Biophys. Acta.* **1639**, 141–151 (2003).
- Kinchen, J. M. *et al.* Two pathways converge at CED-10 to mediate actin rearrangement and corpse removal in *C. elegans*. *Nature* **434**, 93–99 (2005).
- Nagata, S., Hanayama, R. & Kawane, K. Autoimmunity and the clearance of dead cells. *Cell* **140**, 619–630 (2010).
- Mangahas, P. M. & Zhou, Z. Clearance of apoptotic cells in *Caenorhabditis elegans*. *Semin. Cell Dev. Biol.* **16**, 295–306 (2005).
- Albert, M. L., Kim, J. I. & Birge, R. B. α 5 β 1 integrin recruits the CrkII-Dock180-rac1 complex for phagocytosis of apoptotic cells. *Nat. Cell Biol.* **2**, 899–905 (2000).
- Reddien, P. W. & Horvitz, H. R. The engulfment process of programmed cell death in *Caenorhabditis elegans*. *Annu. Rev. Cell Dev. Biol.* **20**, 193–221 (2004).
- Penn, R. B., Pronin, A. N. & Benovic, J. L. Regulation of G protein-coupled receptor kinases. *Trends Cardiovasc. Med.* **10**, 81–89 (2000).
- Premont, R. T. & Gainetdinov, R. R. Physiological roles of G protein-coupled receptor kinases and arrestins. *Annu. Rev. Physiol.* **69**, 511–534 (2007).
- Reiter, E. & Lefkowitz, R. J. GRKs and beta-arrestins: roles in receptor silencing, trafficking and signaling. *Trends Endocrinol. Metab.* **17**, 159–165 (2006).
- Moore, C. A., Milano, S. K. & Benovic, J. L. Regulation of receptor trafficking by GRKs and arrestins. *Annu. Rev. Physiol.* **69**, 451–482 (2007).
- Penela, P., Murga, C., Ribas, C., Lafarga, V. & Mayor, Jr F. The complex G protein-coupled receptor kinase 2 (GRK2) interactome unveils new physiopathological targets. *Br. J. Pharmacol.* **160**, 821–832 (2010).
- Gurevich, E. V., Tesmer, J. J., Mushegian, A. & Gurevich, V. V. G protein-coupled receptor kinases: more than just kinases and not only for GPCRs. *Pharmacol. Ther.* **133**, 40–69 (2012).
- Usui, I. *et al.* G protein-coupled receptor kinase 2 mediates endothelin-1-induced insulin resistance via the inhibition of both Galphaq/11 and insulin receptor substrate-1 pathways in 3T3-L1 adipocytes. *Mol. Endocrinol.* **19**, 2760–2768 (2005).

15. Martini, J. S. *et al.* Uncovering G protein-coupled receptor kinase-5 as a histone deacetylase kinase in the nucleus of cardiomyocytes. *Proc. Natl Acad. Sci. USA* **105**, 12457–12462 (2008).
16. Hoefen, R. J. & Berk, B. C. The multifunctional GIT family of proteins. *J. Cell Sci.* **119**, 1469–1475 (2006).
17. Fehon, R. G., McClatchey, A. I. & Bretscher, A. Organizing the cell cortex: the role of ERM proteins. *Nat. Rev. Mol. Cell Biol.* **11**, 276–287 (2010).
18. Gainetdinov, R. R., Premont, R. T., Caron, M. G. & Lefkowitz, R. J. Reply: receptor specificity of G-protein-coupled receptor kinases. *Trends Pharmacol. Sci.* **21**, 366–367 (2000).
19. Simon, V., Robin, M. T., Legrand, C. & Cohen-Tannoudji, J. Endogenous G protein-coupled receptor kinase 6 triggers homologous beta-adrenergic receptor desensitization in primary uterine smooth muscle cells. *Endocrinology* **144**, 3058–3066 (2003).
20. Penela, P. *et al.* G protein-coupled receptor kinase 2 positively regulates epithelial cell migration. *EMBO J.* **27**, 1206–1218 (2008).
21. Nakaya, M., Tanaka, M., Okabe, Y., Hanayama, R. & Nagata, S. Opposite effects of rho family GTPases on engulfment of apoptotic cells by macrophages. *J. Biol. Chem.* **281**, 8836–8842 (2006).
22. Hall, A. G proteins and small GTPases: distant relatives keep in touch. *Science* **280**, 2074–2075 (1998).
23. Brugnera, E. *et al.* Unconventional Rac-GEF activity is mediated through the Dock180-ELMO complex. *Nat. Cell Biol.* **4**, 574–582 (2002).
24. Park, S. Y. *et al.* Requirement of adaptor protein GULP during stabilin-2-mediated cell corpse engulfment. *J. Biol. Chem.* **283**, 10593–10600 (2008).
25. Premont, R. T. *et al.* Beta2-adrenergic receptor regulation by GIT1, a G protein-coupled receptor kinase-associated ADP ribosylation factor GTPase-activating protein. *Proc. Natl Acad. Sci. USA* **95**, 14082–14087 (1998).
26. Mandiyan, V., Andreev, J., Schlessinger, J. & Hubbard, S. R. Crystal structure of the ARF-GAP domain and ankyrin repeats of PYK2-associated protein beta. *EMBO J.* **18**, 6890–6898 (1999).
27. Premont, R. T. *et al.* The GIT/PIX complex: an oligomeric assembly of GIT family ARF GTPase-activating proteins and PIX family Rac1/Cdc42 guanine nucleotide exchange factors. *Cell Signal* **16**, 1001–1011 (2004).
28. Kosako, H. *et al.* Phosphoproteomics reveals new ERK MAP kinase targets and links ERK to nucleoporin-mediated nuclear transport. *Nat. Struct. Mol. Biol.* **16**, 1026–1035 (2009).
29. Erwig, L. P. *et al.* Differential regulation of phagosome maturation in macrophages and dendritic cells mediated by Rho GTPases and ezrin-radixin-moesin (ERM) proteins. *Proc. Natl Acad. Sci. USA* **103**, 12825–12830 (2006).
30. Matsui, T. *et al.* Rho-kinase phosphorylates COOH-terminal threonines of ezrin/radixin/moesin (ERM) proteins and regulates their head-to-tail association. *J. Cell Biol.* **140**, 647–657 (1998).
31. Mangeat, P., Roy, C. & Martin, M. ERM proteins in cell adhesion and membrane dynamics. *Trends Cell Biol.* **9**, 187–192 (1999).
32. Elliott, M. R. & Ravichandran, K. S. Clearance of apoptotic cells: implications in health and disease. *J. Cell Biol.* **189**, 1059–1070 (2010).
33. Hanayama, R. *et al.* Autoimmune disease and impaired uptake of apoptotic cells in MFG-E8-deficient mice. *Science* **304**, 1147–1150 (2004).
34. Peng, Y. & Elkon, K. B. Autoimmunity in MFG-E8-deficient mice is associated with altered trafficking and enhanced cross-presentation of apoptotic cell antigens. *J. Clin. Invest.* **121**, 2221–2241 (2011).
35. Sallusto, F., Geginat, J. & Lanzavecchia, A. Central memory and effector memory T cell subsets: function, generation, and maintenance. *Annu. Rev. Immunol.* **22**, 745–763 (2004).
36. Mukundan, L. *et al.* PPAR-delta senses and orchestrates clearance of apoptotic cells to promote tolerance. *Nat. Med.* **15**, 1266–1272 (2009).
37. A-Gonzalez, N. *et al.* Apoptotic cells promote their own clearance and immune tolerance through activation of the nuclear receptor LXR. *Immunity* **31**, 245–258 (2009).
38. McEvoy, L., Williamson, P. & Schlegel, R. A. Membrane phospholipid asymmetry as a determinant of erythrocyte recognition by macrophages. *Proc. Natl Acad. Sci. USA* **83**, 3311–3315 (1986).
39. Connor, J., Pak, C. C. & Schroit, A. J. Exposure of phosphatidylserine in the outer leaflet of human red blood cells. Relationship to cell density, cell age, and clearance by mononuclear cells. *J. Biol. Chem.* **269**, 2399–2404 (1994).
40. Kohyama, M. *et al.* Role for Spi-C in the development of red pulp macrophages and splenic iron homeostasis. *Nature* **457**, 318–321 (2009).
41. Chow, A. *et al.* Bone marrow CD169+ macrophages promote the retention of hematopoietic stem and progenitor cells in the mesenchymal stem cell niche. *J. Exp. Med.* **208**, 261–271 (2011).
42. Hashimoto, D. *et al.* Pretransplant CSF-1 therapy expands recipient macrophages and ameliorates GVHD after allogeneic hematopoietic cell transplantation. *J. Exp. Med.* **208**, 1069–1082 (2011).
43. Tolosano, E. *et al.* Enhanced splenomegaly and severe liver inflammation in haptoglobin/hemopexin double-null mice after acute hemolysis. *Blood* **100**, 4201–4208 (2002).
44. Lafarga, V., Aymerich, I., Tapia, O., Mayor, Jr F. & Penela, P. A novel GRK2/HDAC6 interaction modulates cell spreading and motility. *EMBO J.* **31**, 856–869 (2012).
45. Ribas, C. *et al.* The G protein-coupled receptor kinase (GRK) interactome: role of GRKs in GPCR regulation and signaling. *Biochim. Biophys. Acta.* **1768**, 913–922 (2007).
46. Cant, S. H. & Pitcher, J. A. G protein-coupled receptor kinase 2-mediated phosphorylation of ezrin is required for G protein-coupled receptor-dependent reorganization of the actin cytoskeleton. *Mol. Biol. Cell* **16**, 3088–3099 (2005).
47. Oldenborg, P. A. *et al.* Role of CD47 as a marker of self on red blood cells. *Science* **288**, 2051–2054 (2000).

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Author contributions

M.Na. designed research. M.Na., M.T., A.H., M.O. and S.K. prepared DNA constructs and performed phagocytosis assay, immunoblotting and immunoprecipitation. M.Na., M.T., A.H. and M.O. conducted phalloidin staining and Rac1 pull-down assay. M.Na. and A.H. carried out enzyme-linked immunosorbent assay experiments and analysed spleen cell population by flow cytometer. Two-dimensional difference gel electrophoresis and *in vitro* kinase assay were performed by H.Ko. Protein identification by mass spectrometry was done by H.Ko., N.T., H.T. and M.M. M.Na., T.N., M.T., K.W., M.K. and H.N. stained spleen and kidney sections. M.Na. conducted all the other experiments. H.Ko., M.Ni., Y.S., M.T. and K.I. provided key reagents and intellectual inputs. M.Na. and H.Ku. wrote the paper.

Additional information

Supplementary Information accompanies this paper at <http://www.nature.com/naturecommunications>

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Stem Cell Research for Regenerative Medicine/Personalized Medicine

Tumorigenicity Studies for Human Pluripotent Stem Cell-Derived Products

Takuya Kuroda,^{a,b} Satoshi Yasuda,^{a,b} and Yoji Sato^{*a,b,c}^a Division of Cellular and Gene Therapy Products, National Institute of Health Sciences; 1-18-1 Kamiyoga, Setagaya-ku, Tokyo 158-8501, Japan:^b Foundation for Biomedical Research and Innovation; Kobe 650-0047, Japan: and^c Department of Quality Assurance Science for Pharmaceuticals, Graduate School of Pharmaceutical Sciences, Nagoya City University; Nagoya 467-8603, Japan.

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Human pluripotent stem cells (hPSCs), *i.e.* human embryonic stem cells and human induced pluripotent stem cells, are able to self-renew and differentiate into multiple cell types. Because of these abilities, numerous attempts have been made to utilize hPSCs in regenerative medicine/cell therapy. hPSCs are, however, also tumorigenic, that is, they can give rise to the progressive growth of tumor nodules in immunologically unresponsive animals. Therefore, assessing and managing the tumorigenicity of all final products is essential in order to prevent ectopic tissue formation, tumor development, and/or malignant transformation elicited by residual pluripotent stem cells after implantation. No detailed guideline for the tumorigenicity testing of hPSC-derived products has yet been issued for regenerative medicine/cell therapy, despite the urgent necessity. Here, we describe the current situations and issues related to the tumorigenicity testing of hPSC-derived products and we review the advantages and disadvantages of several types of tumorigenicity-associated tests. We also refer to important considerations in the execution and design of specific studies to monitor the tumorigenicity of hPSC-derived products.

Key words pluripotent stem cell; embryonic stem cell; induced pluripotent stem cell; tumorigenicity; regenerative medicine; cell therapy

1. INTRODUCTION

Pluripotent stem cells, such as embryonic stem cells (ESCs) and induced pluripotent stem cells (iPSCs), have two abilities: 1) pluripotency, which is the ability to differentiate into a variety of cells, and 2) self-renewal, which is the ability to undergo numerous cell division cycles while maintaining their cellular identity. Because of these two characteristics, they are expected to provide new sources for the robust and continuous production of a variety of cells and tissues for use in regenerative medicine/cell therapy. Additionally, human iPSCs (hiPSCs) offer a possible solution to the ethical problems and immune rejection of cell products derived from human ESCs (hESCs), thus creating novel avenues for individual patient-specific cell therapy. As a practical example of therapy using hESC-based products, the world's first clinical trial started in spinal cord patients in the United States in 2011. Other clinical trials have also been conducted with retinal pigment epithelial (RPE) cells derived from hESCs to treat patients with dry age-related macular degeneration (AMD) and Stargardt's macular dystrophy by Advanced Cell Technology.¹⁾ Following Yamanaka's establishment of hiPSCs in 2007, new innovations in regenerative medicine/cell therapy have been made that relate to cell substrates, manufacturing materials, and application methods. As one of the promising seeds for practical use in regenerative medicine/cell therapy, the clinical application of hiPSC-derived RPE cells is expected to start in 2013 in

Japan for wet AMD patients.

For the proper development of hPSC-derived products, it is essential to assess their risk and to study their quality and safety. In this review, we place a particular focus on the current situations and issues related to the evaluation of tumorigenicity, which is one of the potential concerns in an attempt to conduct clinical research on hPSC-derived products.

2. THE TUMORIGENICITY OF HUMAN PLURIPOTENT STEM CELLS

Tumorigenicity is defined as the capacity of a cell population inoculated into an animal model to produce a tumor by proliferation at the site of inoculation and/or at a distant site by metastasis.²⁾ Undifferentiated hPSCs have the ability to form teratoma in animals, and this is ascribed to their pluripotency.³⁾ In general, to demonstrate the pluripotency of established cells, they are injected into immunodeficient mice, *e.g.*, nude mice, to form spontaneous teratomas. Teratomas are defined as tumors of multiple lineages containing tissue derived from the three germ layers (*i.e.*, endoderm, mesoderm, and ectoderm). hPSCs are tumorigenic and differ greatly from somatic cells and somatic stem cells in terms of tumorigenic potential.⁴⁾ Residual pluripotent cells in hPSC-derived products have the ability to initiate ectopic tissue formation, tumor development, and/or malignant transformation.

The authors declare no conflict of interest.

* To whom correspondence should be addressed. e-mail: yoji@nihs.go.jp

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3. INTERNATIONAL GUIDELINES OF TUMORIGENICITY STUDIES

At present, the World Health Organization (WHO) TRS 878 guideline, titled, "Recommendations for the evaluation of animal cell cultures as substrates for the manufacture of biological medicinal products and for the characterization of cell banks,"^{2,5)} is the only international guideline addressing tumorigenicity studies. The International Conference on Harmonization's "ICH guideline Q5D: Derivation and Characterisation of Cell Substrates Used for Production of Biotechnological/Biological Products" also cited the tumorigenicity tests of the WHO TRS 878 guideline. These guidelines provide documented study design advice and general principles for tumorigenicity studies. Several *in vitro* test systems, such as cell growth in soft agar and muscle organ culture, have been explored as alternatives to *in vivo* tests for tumorigenicity⁶⁾; however, as a result of technical difficulties, the correlations with *in vivo* tests have not yet been clearly proved. Therefore, in the WHO TRS 878, *in vivo* tests remain the standard for assessing tumorigenicity. Simply put, the model protocol of the *in vivo* tumorigenicity test in the WHO TRS 878 is that 10^7 animal cells are administered to 10 nude mice and observed for 3 to 16 weeks; HeLa cells are recommended as the positive control reference preparation. Applying this test to hPSC-based cell therapy products, we must learn about its coverage and purpose. The *in vivo* tumorigenicity test proposed in WHO TRS 878 covers cells used to manufacture biological products but not cells transplanted into patients. Its purpose is to examine the tumorigenic phenotype range, from non-tumorigenic to weakly- or highly tumorigenic, of the cell banks, but not to detect the slightly contaminated tumorigenic cells in hPSC-derived products. The WHO TRS 878 also requires the master or working cell bank to check the tumorigenicity whenever cultured for predetermined passage times. WHO TRS 878 has therefore not directly addressed the tumorigenicity of hPSC-derived products. Importantly, the tumorigenicity described in WHO TRS 878 is not a direct risk index for humans but that estimated by animal testing, which examines tumor formation at transplanted sites and metastasis at remote sites.

4. ALTERNATIVE APPLICATION OF WHO TRS 878 TO hPSC-DERIVED PRODUCTS

As mentioned above, one of the risks of hPSC-derived products is the possibility of tumor formation following transplantation. To ensure safety, the tumorigenicity of hPSC-derived products must be evaluated to identify undifferentiated and/or abnormal cells that might exist in minute quantities in final products. It should be noted that the tumorigenicity of final products is clearly different from the tumorigenicity of the cell bank of serially passaged cell lines defined as cell substrates in WHO TRS 878. However, we must consider how the WHO TRS 878 protocol of tumorigenicity testing should be applied to hPSC-derived products because the WHO TRS878 guideline is the only one that directly addresses tumorigenicity studies. First, we understand the grounds of the WHO TRS 878 tumorigenicity test protocol to require administration of 10^7 cells to nude mice. Tumor-producing doses at the 50% endpoint (TPD₅₀) (the number of cells required for

tumor development with 50% probability) are used as units of tumorigenic phenotypes. The strengths of TPD₅₀ vary greatly according to cell strain. For example, the TPD₅₀ values of Endo-CA (human endometrial carcinoma cells), A594 (human lung cancer cells), HeLa (human cervical carcinoma cells), and 293 (human kidney cells) are 10 , 3×10^3 , 3×10^4 and 3×10^6 cells/nude mouse, respectively.⁷⁾ Administering 10^7 cells to 10 nude mice should result in the tumor formation of 293 weakly tumorigenic cells in several nude mice out of ten. On the other hand, 10^7 cells of highly tumorigenic HeLa cells should form tumors in all ten nude mice. Therefore, HeLa cells are recommended as the positive control.

In general, treatment with hPSCs-derived products is thought to require from several tens of thousands to hundreds of millions cells, depending on the disease. Several tens of thousands of prepared RPE cells may be required for retinal degeneration diseases, whereas in the case of treatment for heart failure, hundreds of millions of cardiac muscle cells may be necessary. Assuming that 1 in 10^4 of the final product cells (0.1%) is tumorigenic, the *in vivo* tumorigenicity test would require an inoculum of 3×10^8 or 3×10^{10} cells to detect tumor formation in nude mice when contaminated cells have tumorigenic activity equal to HeLa cells (TPD₅₀: 3×10^4) or 293 cells (TPD₅₀: 3×10^6), respectively. The alternative application of WHO TRS 878 "Administrate 10^7 cells to 10 nude mice" to hPSC-derived products may thus lead to false-negative test results.

5. AVAILABILITY OF HIGHLY IMMUNODEFICIENT MICE

To detect slightly contaminated tumorigenic cells in hPSC-derived products, several new generations of severely immunodeficient animal models are now available. Rag2- γ C double-knockout (DKO) mice,⁸⁾ NOD/SCID/ γ C^{null} (NOG) mice,⁹⁾ and NOD/SCID/IL-2rgKO (NSG) mice¹⁰⁾ are reported to be T, B, and NK cell-defective and to show high engraftment rates of human cells and tissues compared with traditional nude (T cell-defective) mice.^{11,12)} Using these severe combined immunodeficient mouse lines, which are likely to be useful for sensitive *in vivo* tumorigenicity tests, the small amount of residual tumorigenic cells in the hPSC-derived products could be detected. Since scientific risk assessment needs to standardize the tumorigenicity evaluation of hPSC-derived products, the following points should be taken into consideration in the development of *in vivo* tumorigenicity tests: (a) validation of the limit of detection, sensitivity, and precision, (b) positive and negative control selection, (c) number of tested cells, (d) test duration, (e) route/method of administration, and (f) comparison with nude mouse.

6. *IN VITRO* TUMORIGENICITY-ASSOCIATED TESTS

Some tests are indicated to detect tumorigenic cells contaminating cell populations *in vitro*. Table 1 summarizes the advantages and disadvantages of the tests associated with product tumorigenicity. The soft agar colony formation assay is a conventional method to monitor anchorage-independent growth, and is considered the most appropriate *in vitro* assay to detect the malignant transformation of cells.⁶⁾ Previous

Table 1. Comparison of Tumorigenicity-Associated Assays

Assay	Soft agar colony formation assay	Flow cytometry	qRT-PCR	<i>In vivo</i> tumorigenicity test using SCID mice ¹⁵⁾
Measurement standard	Colony formation	Expression of marker protein for pluripotency	Expression of marker gene for pluripotency	Tumor formation
Purpose	Detection of anchorage-independent growth	Detection of tumorigenic and undifferentiated cell	Detection of tumorigenic and undifferentiated cells	Detection of tumorigenic of undifferentiated pluripotent cells
Time	30 d	1 d	6 h	12–16 weeks
Advantage	Inexpensive	Rapid Analyzes individual cells	Rapid and simple Quantitative	Direct Analyzes tumor formation in a specific microenvironment
Disadvantage	Indirect Not applicable to hiPSCs	Indirect Detects only the cells that express the known marker proteins Gating techniques strongly influence the results	Highly sensitive Indirect Detects only the cells that express the known marker genes	Costly Time-consuming
Limit of detection	1% of PA-1 teratocarcinoma cells	0.1% of hiPSCs (TRA-1-60)	≤0.002% of hiPSCs (Lin28)	245 Undifferentiated hESCs with 10 ⁶ feeder fibroblasts (0.025%)

reports have shown that hPSCs undergo apoptosis when dissociated into single cells.¹³⁾ This test requires the scattering of cells and their enclosure in agar so it may be difficult to utilize it for tests of hPSC-derived product tumorigenicity. Flow cytometry and quantitative reverse transcription polymerase chain reaction (qRT-PCR) tests were found to be able to detect a trace amount of undifferentiated cells. The advantage of the flow cytometry test is that it can be used to identify undifferentiated cells. Unfortunately, the results are greatly affected by gating, and only the cells expressing the marker proteins are detectable. The advantages of qRT-PCR are its rapidity, quantitative nature, and high sensitivity. Its disadvantage is that only the cells expressing the marker gene are detectable. Our previous report demonstrated that the soft agar colony formation assay is unable to detect hiPSCs, even in the presence of a Rho-associated protein kinase (ROCK) inhibitor that permits survival of dissociated hiPSCs/hESCs. The flow cytometry test using anti-TRA-1-60 antibody has detected 0.1% undifferentiated hiPSCs spiked in primary RPE cells. The qRT-PCR method with a specific probe and primers has been found to detect a trace amount of Lin28 mRNA, which is equivalent to that present in a mixture of a single hiPSC and 5×10⁴ RPE cells.¹⁴⁾ As tumorigenic cells are commonly highly proliferative and immortalized, observation of the cell growth rate by culturing for a limited period also seems to be useful to detect rapidly growing contaminated immortalized cells. If combinations of these *in vitro* tumorigenicity-associated tests do not demonstrate the existence of both undifferentiated and immortalized cells, the tumorigenic potential of final products can be considered extremely low. More importantly, the validity of advancing to clinical trials should be confirmed for each product and judged by the following points: (a) methods of cell inoculum, (b) sites of injection, (c) risk management plans, (d) results from *in vivo* tumorigenicity tests.

7. CONCLUSION AND FUTURE PROSPECTS

No guideline for the tumorigenicity testing of cell-/

tissue-derived products, including hPSC-derived products, has been issued. Because the subject and purpose described in WHO TRS 878 are not suitable for hPSC-derived products, the direct application of the WHO TRS 878 tumorigenicity test to hPSC-derived products is unreasonable. Tumorigenicity studies for hPSC-based products should examine (a) the existence of residual undifferentiated pluripotent cells, (b) the existence of tumorigenic transformants, and (c) whether the transplant forms tumor in microenvironments at the site of transplantation. As a countermeasure, highly sensitive *in vivo* tumorigenicity tests using severely immunodeficient mice may be a viable option. We now address the current problems with the development and standardization of *in vivo* tumorigenicity tests for hPSC-derived products.

Safety assessments of hPSC-derived products must choose among various tumorigenicity tests, considering the limitations of each. The overall safety of each product should be estimated on the basis of the results of an appropriate set of tumorigenicity tests. The following points should also be taken into account in order to decide on the items to evaluate: (a) properties of the raw materials, (b) properties of the products, (c) target diseases, and (d) risk management. Of course, the results/assessments of even the most appropriate tumorigenicity tests cannot guarantee safety in humans. After understanding the limitation of each tumorigenicity test, we should develop a risk assessment and risk management plan and obtain informed patient consent.

REFERENCES

- 1) Schwartz SD, Hubschman JP, Heilwell G, Franco-Cardenas V, Pan CK, Ostrick RM, Mickunas E, Gay R, Klimanskaya I, Lanza R. Embryonic stem cell trials for macular degeneration: a preliminary report. *Lancet*. 379, 713–720 (2012).
- 2) World Health Organization. "Recommendations for the evaluation of animal cell cultures as substrates for the manufacture of biological medicinal products and for the characterization of cell banks. Proposed replacement of TRS 878, Annex 1.": <<http://www.who.int/>

- biologicals/BS2132-CS_Recommendations_CLEAN_19_July_2010.pdf, cited 19 July, 2010.
- 3) Müller FJ, Goldmann J, Löser P, Loring JF. A call to standardize teratoma assays used to define human pluripotent cell lines. *Cell Stem Cell*, **6**, 412–414 (2010).
 - 4) Prockop DJ. Defining the probability that a cell therapy will produce a malignancy. *Mol. Ther.*, **18**, 1249–1250 (2010).
 - 5) World Health Organization. "Requirements for the use of animal cells as *in vitro* substrates for the production of biologicals. WHO Technical Report Series No.878, Annex 1." (http://whglibdoc.who.int/trs/WHO_TRS_878.pdf), cited 1998.
 - 6) Hamburger AW, Salmon SE. Primary bioassay of human tumor stem cells. *Science*, **197**, 461–463 (1977).
 - 7) Lewis AM. "Regulatory Implications of Neoplastic Cell Substrate Tumorigenicity." (http://www.fda.gov/ohrms/dockets/ac/05/slides/5-4188S1_2.ppt), cited 2005.
 - 8) Garcia S, DiSanto J, Stockinger B. Following the development of a CD4 T cell response *in vivo*: from activation to memory formation. *Immunity*, **11**, 163–171 (1999).
 - 9) Ito M, Hiramatsu H, Kobayashi K, Suzue K, Kawahata M, Hioki K, Ueyama Y, Koyanagi Y, Sugamura K, Tsuji K, Heike T, Nakahata T. NOD/SCID/gamma(c)(null) mouse: an excellent recipient mouse model for engraftment of human cells. *Blood*, **100**, 3175–3182 (2002).
 - 10) Ishikawa F, Yasukawa M, Lyons B, Yoshida S, Miyamoto T, Yoshimoto G, Watanabe T, Akashi K, Shultz LD, Harada M. Development of functional human blood and immune systems in NOD/SCID/IL2 receptor gamma chain(null) mice. *Blood*, **106**, 1565–1573 (2005).
 - 11) Machida K, Suemizu H, Kawai K, Ishikawa T, Sawada R, Ohnishi Y, Tsuchiya T. Higher susceptibility of NOG mice to xenotransplanted tumors. *J. Toxicol. Sci.*, **34**, 123–127 (2009).
 - 12) Quintana E, Shackleton M, Sabel MS, Fullen DR, Johnson TM, Morrison SJ. Efficient tumour formation by single human melanoma cells. *Nature*, **456**, 593–598 (2008).
 - 13) Watanabe K, Ueno M, Kamiya D, Nishiyama A, Matsumura M, Wataya T, Takahashi JB, Nishikawa S, Nishikawa S, Muguruma K, Sasai Y. A ROCK inhibitor permits survival of dissociated human embryonic stem cells. *Nat. Biotechnol.*, **25**, 681–686 (2007).
 - 14) Kuroda T, Yasuda S, Kusakawa S, Hirata N, Kanda Y, Suzuki K, Takahashi M, Nishikawa S, Kawamata S, Sato Y. Highly sensitive *in vitro* methods for detection of residual undifferentiated cells in retinal pigment epithelial cells derived from human iPS cells. *PLoS ONE*, **7**, e37342 (2012).
 - 15) Hentze H, Soong PL, Wang ST, Phillips BW, Putti TC, Dunn NR. Teratoma formation by human embryonic stem cells: evaluation of essential parameters for future safety studies. *Stem Cell Res. (Amst.)*, **2**, 198–210 (2009).

Induction of Cardiac Fibrosis by β -Blocker in G Protein-independent and G Protein-coupled Receptor Kinase 5/ β -Arrestin2-dependent Signaling Pathways*[§]

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Michio Nakaya[‡], Satsuki Chikura[‡], Kenji Watari[‡], Natsumi Mizuno[‡], Koji Mochinaga[‡], Supachoke Mangmool[‡], Satoru Koyanagi[§], Shigehiro Ohdo[§], Yoji Sato[¶], Tomomi Ide^{||}, Motohiro Nishida[‡], and Hitoshi Kurose^{†1}

From the Departments of [‡]Pharmacology and Toxicology and [§]Pharmaceutical Sciences, Graduate School of Pharmaceutical Sciences, and the ^{||}Department of Cardiovascular Medicine, Graduate School of Medical Sciences, Kyushu University, Fukuoka 812-8582 and the [¶]Division of Cellular and Gene Therapy Products, National Institute of Health Sciences, Setagaya, Tokyo 158-8501, Japan

Background: It is not known whether a β -blocker, metoprolol, induces physiological responses through β -arrestins *in vivo*.
Results: Long-term administration of metoprolol induced cardiac fibrosis in wild type but not β -arrestin2- or GRK5 knock-out mice.
Conclusion: Metoprolol induced cardiac fibrosis in a G protein-independent and GRK5/ β -arrestin2-dependent manner.
Significance: Our study provides a physiological significance of β -arrestin-mediated biased signaling pathway by a β -blocker *in vivo*.

G-protein coupled receptors (GPCRs) have long been known as receptors that activate G protein-dependent cellular signaling pathways. In addition to the G protein-dependent pathways, recent reports have revealed that several ligands called “biased ligands” elicit G protein-independent and β -arrestin-dependent signaling through GPCRs (biased agonism). Several β -blockers are known as biased ligands. All β -blockers inhibit the binding of agonists to the β -adrenergic receptors. In addition to β -blocking action, some β -blockers are reported to induce cellular responses through G protein-independent and β -arrestin-dependent signaling pathways. However, the physiological significance induced by the β -arrestin-dependent pathway remains much to be clarified *in vivo*. Here, we demonstrate that metoprolol, a β_1 -adrenergic receptor-selective blocker, could induce cardiac fibrosis through a G protein-independent and β -arrestin2-dependent pathway. Metoprolol, a β -blocker, increased the expression of fibrotic genes responsible for cardiac fibrosis in cardiomyocytes. Furthermore, metoprolol induced the interaction between β_1 -adrenergic receptor and β -arrestin2, but not β -arrestin1. The interaction between β_1 -adrenergic receptor and β -arrestin2 by metoprolol was impaired in the G protein-coupled receptor kinase 5 (GRK5)-knockdown cells. Metoprolol-induced cardiac fibrosis led to cardiac dysfunction. However, the metoprolol-induced fibrosis and cardiac dysfunction were not evoked in β -arrestin2- or GRK5-knock-out mice. Thus, metoprolol is a biased ligand that selectively activates a G protein-independent and GRK5/ β -ar-

restin2-dependent pathway, and induces cardiac fibrosis. This study demonstrates the physiological importance of biased agonism, and suggests that G protein-independent and β -arrestin-dependent signaling is a reason for the diversity of the effectiveness of β -blockers.

G protein-coupled receptors (GPCRs)² mediate physiological responses to a variety of ligands, such as hormones, neurotransmitters, and environmental stimuli, and are tightly regulated by several mechanisms (1). Among the mechanisms, GPCR kinase (GRK) and β -arrestin-mediated events are known as general mechanisms of GPCR functional regulation (2–6). When an agonist binds to GPCR, it activates a cellular signal transduction cascade through G proteins, but also induces GRK/ β -arrestin-mediated events to prevent excess stimulation. GRKs phosphorylate the agonist-bound GPCRs, and β -arrestins bind to the phosphorylated receptors, and then inhibit further stimulation of G proteins by the agonist-bound receptors through steric hinderance. As β -arrestins can also bind clathrin and adaptor proteins, the phosphorylated and β -arrestin-bound receptors are internalized into endocytic vesicles (7). The internalized receptors then are recycled back to the plasma membrane or directed to the degradation pathway by undefined processes (8, 9). In addition to the receptor regulation, it has been recently recognized that GRKs and β -arrestins mediate cellular signaling by GPCRs independently of G protein activation (2–4, 10, 11). However, these GRK- and β -arrestin-dependent signaling pathways are largely demonstrated by *in vitro* cellular systems. To establish the physiological impor-

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¹ To whom correspondence should be addressed: Kyushu University, 3-1-1 Maidashi, Higashi-ku, Fukuoka 812-8582, Japan. Tel./Fax: 81-92-642-6884; E-mail: kurose@phar.kyushu-u.ac.jp.

² The abbreviations used are: GPCR, G protein-coupled receptor; GRK, G protein-coupled receptor kinase; BRET, bioluminescence resonance energy transfer; FRET, fluorescence resonance energy transfer; CTGF, connective tissue growth factor; Col1a, collagen 1 α ; Rluc, *Renilla* luciferase; KO, knockout.

GRK5/ β -Arrestin2-mediated Cardiac Fibrosis

tance of the signaling pathways, it is essential to demonstrate GRK- and β -arrestin-dependent responses *in vivo*.

β -Adrenergic receptors are members of the G protein-coupled receptor family and are pharmacologically and genetically subdivided into three subtypes: β_1 , β_2 , and β_3 (12). The β_1 -adrenergic receptor is involved in the regulation of cardiac functions as well as in the induction and development of various cardiovascular diseases including heart failure (13, 14). During heart failure, a large amount of catecholamine is believed to be released from synaptic ends (15, 16), and exerts harmful effects on the heart. Therefore, administration of β -adrenergic receptor antagonists, β -blockers, is effective for patients in the early stages of heart failure (17). So far, various kinds of β -blockers have been developed, but many basic and clinical studies indicate that the effect of each β -blocker is divergent (18). Several reasons, including receptor selectivity, antioxidant property, and membrane-stabilizing effects have been proposed for the diversity, but there still remains much to be known. Understanding the reasons more properly would help to develop a more efficient β -blocker with fewer side effects.

In addition to the blocking effects, some β -blockers have been shown to evoke signal transduction through the β -adrenergic receptors in G protein-independent and β -arrestin-dependent manner (19–21). Like β -blockers, some agonists for seven-transmembrane receptors have been reported not only to transmit the classic G protein signaling, but also to generate the signaling in a G protein-independent fashion (22–25). These agonists and phenomena are called “biased ligands” and “biased agonism,” respectively (11). To date, the signal transduction pathways by biased ligands have been intensively unveiled by *in vitro* studies. However, the physiological meaning of the biased ligand-mediated signaling is hardly clarified *in vivo*.

We found that long-term administration of metoprolol, an inverse agonist for the β_1 -adrenergic receptor, to mice induced cardiac fibrosis, which is thought to be deleterious for the heart by stiffening it and inhibiting the electrical conductivity between cardiomyocytes. We revealed that this fibrotic pathway was mediated through the β_1 -adrenergic receptor in a G protein-independent manner. We also discovered that β -arrestin2 and GRK5 are involved in this G protein-independent fibrotic pathway not only *in vitro* but also *in vivo*.

EXPERIMENTAL PROCEDURES

Animals and Administration of β -Blockers—We purchased ddY, C57BL/6J mice, and Sprague-Dawley rats from KYUDO (Japan). GRK5-, GRK6-, and β -arrestin2-KO mice were obtained by Drs. R. J. Lefkowitz and R. T. Premont (Duke University). Administration of β -blockers was started at 6 weeks of age of male mice. β -Blockers (metoprolol, 30 mg/kg/day; carvedilol, 30 mg/kg/day; propranolol, 10 mg/kg/day) or saline were orally administered twice a day for 3 months. All experiments using mice and rats were approved by the guidelines of Kyushu University.

Isolation of Cardiac Cells and Transfection—Rat neonatal cardiomyocytes and cardiac fibroblasts were isolated as described previously (26, 27). In brief, 1-day-old Sprague-Dawley rats are deeply anesthetized and their hearts were expedi-

tiously extirpated on ice. The atria of the extirpated hearts are quickly removed by using sterilized forceps and scissors. The remaining hearts were cut into small pieces and digested by collagenase. The digested cells were plated on 10-cm plates for 1 h at 37 °C and nonattached cells or attached cells were used as cardiomyocytes or cardiac fibroblasts, respectively. The cardiomyocytes are plated on gelatin-coated 6-well plates (3×10^4 cells/well). When siRNAs were transfected into cardiomyocytes, Lipofectamine 2000 was used. Plasmid DNAs were transfected into the rat neonatal cardiomyocytes or H9c2 cells by electroporation and into HEK293 cells by FuGENE6 (Roche Applied Science).

BRET Assay—To evaluate the interaction between β_1 -adrenergic receptor and β -arrestin2, or the conformational changes in β -arrestin2, BRET experiments were performed as described previously (28, 29). The plasmids of β_1 -adrenergic receptor-Rluc, GFP²- β -arrestin1, and β -arrestin2-GFP² were transfected into HEK293 cells, H9c2 cells, or rat neonatal cardiomyocytes. Rluc- β -arrestin2-GFP² was expressed in HEK293 or H9c2 cells. These cells stably expressed the β_1 -adrenergic receptor. Forty-eight hours after the transfection, the cells were collected and washed by DMEM/F12 (Invitrogen). The cells were suspended in the assay buffer (0.1 g/liter of CaCl₂, 0.1 g/liter of MgCl₂·6H₂O, 1 g/liter of D-glucose, and 2 μ g/ml of aprotinin in PBS) to adjust 5×10^4 cells/ml. Then, 25 μ l of the cell suspension was distributed in a 96-well white microplate and 25 μ l of the drug solution was added. After a 5-min incubation, DeepBlueCTM was added at a final concentration of 5 μ M and the 400 nm (Rluc) and 515 nm (GFP²) emissions were immediately measured using a Multilabel Reader Mithras LB 940 (Berthold Technologies).

FRET Assay—The FRET probe to monitor the changes of the concentration of cAMP was constructed as reported previously (30). HEK293 cells stably overexpressing the β_1 -adrenergic receptor were plated on poly-L-lysine-coated 35-mm glass-bottom base dishes and transfected with the FRET probe. Two days after transfection, the culture medium was replaced by phenol red-free medium (DMEM/F-12) containing 0.1% fetal bovine serum, and more than 3 h later, the cells were imaged by the microscopy (Olympus IX-81) in a heated chamber kept at 37 °C. In some experiments of β -blocker stimulation, drugs other than β -blockers were added before the stimulation. ICI118551 (50 μ M) or pertussis toxin (100 ng/ml) were added 10 min or 16 h before the stimulation of β -blockers, respectively. 3-Isobutyl-1-methylxanthine (1 mM) was added simultaneously with each β -blocker. The images for CFP, YFP, and DIC were taken every 1 min. Image analysis was performed by MetaMorph software (Universal imaging).

Histological Analysis—Hearts from mice were extirpated and fixed by paraformaldehyde. The fixed hearts were embedded and sectioned (3 μ m thickness). The heart sections were stained with hematoxylin and eosin (H&E), Masson's trichrome, or picosirius red. The digital images for the stained sections were taken by a Biozero microscope (BZ-8000, Keyence). The degree of fibrosis in the images was estimated by BZ-analyzer (BZ-9000, Keyence).

Real Time RT-PCR—Total RNA was extracted from mouse hearts using RNeasy fibrous tissue kit (Qiagen) according to the