Abcg2 labels multiple cell types in skeletal muscle and participates in muscle regeneration

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Skeletal muscle contains progenitor cells (satellite cells) that maintain and repair muscle. It also contains muscle side population (SP) cells, which express Abcg2 and may participate in muscle regeneration or may represent a source of satellite cell replenishment. In Abcg2-null mice, the SP fraction is lost in skeletal muscle, although the significance of this loss was previously unknown. We show that cells expressing Abcg2 increased upon injury and that muscle regeneration was impaired in Abcg2-null mice, resulting in fewer centrally nucleated myofibers, reduced myofiber size, and fewer satellite cells. Additionally, using genetic lineage tracing, we demonstrate that the progeny of Abcg2-expressing cells contributed to multiple cell types within the muscle interstitium, primarily endothelial cells. After injury, Abcg2 progeny made a minor contribution to regenerated myofibers. Furthermore, Abcg2-labeled cells increased significantly upon injury and appeared to traffic to muscle from peripheral blood. Together, these data suggest an important role for Abcg2 in positively regulating skeletal muscle regeneration.

Introduction

Skeletal muscle has a remarkable capacity to respond to pathological stress and regenerate upon injury. Skeletal muscle consists of postmitotic, multinucleated myofibers as well as mononuclear cells, including muscle progenitor cells (satellite cells) and other less well-characterized interstitial cells. Muscle regeneration is dependent on satellite cells, which in response to injury undergo proliferation, differentiation, and ultimately, fusion with new or existing myofibers to repair the muscle. Recently, the importance of other cell types located within the muscle interstitium has gained interest. Many of these, such as muscle side population (SP) cells, PW1+/Pax7− cells, vascular-associated pericytes, and myoendothelial cells have been reported to possess myogenic potential (Asakura et al., 2002; Dellavalle et al., 2007; Zheng et al., 2007; Tanaka et al., 2009; Mitchell et al., 2010). Others, including endothelial cells and fibroadipogenic progenitors (FAPs), positively regulate myogenesis (Abou-Khalil et al., 2010; Joe et al., 2010). In addition to these resident muscle cells, substantial evidence suggests regulatory interactions of the immune response with skeletal muscle play a significant role in regeneration (Tidball and Villalta, 2010).

Previous studies suggest that muscle SP cells may be precursors of the satellite cell population or may be independent progenitor cells that participate in muscle regeneration. The SP phenotype is defined by the ability of cells to efflux Hoechst 33342 dye. Abcg2, a member of the ATP-binding cassette (ABC) transporter family, effluxes Hoechst 33342 dye and is actively exporting multiple drugs and protects cells from apoptosis under cases of hypoxia and oxidative stress (Krishnamurthy et al., 2004; Krishnamurthy and Schuetz, 2006; Martin et al., 2008). Multiple tissues, including muscle, contain SP cells positive for Abcg2. In adult skeletal muscle, Abcg2-positive cells are closely localized to the vasculature (Meeson et al., 2004; Huls et al., 2009). Although previous studies show that muscle SP cells engraft into regenerating myofibers upon intramuscular transplantation (Asakura et al., 2002; Meeson et al., 2004; Tanaka et al., 2009), the fate of endogenous...
muscle SP cells has not been traced in vivo, and so much about their identity and potential remains unknown. Upon genetic deletion of Abcg2, muscle SP cells are lost (Zhou et al., 2002), although the consequence of this loss on muscle regeneration has not been tested.

In the present study, we analyze the functional consequence of germline deletion of Abcg2 on muscle regeneration and show that muscle regeneration is delayed, resulting in fewer myonuclei and smaller caliber myofibers as well as a decrease in Pax7-positive satellite cells. Additionally, we followed the fate of Abcg2-positive cells in skeletal muscle in vivo using genetic lineage tracing driven by Abcg2 expression. Using this approach, we demonstrate that Abcg2-labeled cells contribute primarily to vascular-associated interstitial cells, including endothelial cells and pericytes. Upon injury, Abcg2-labeled progeny increases, although under these conditions, they are not a major contributor to myonuclei. We further show that the immune response is compromised in Abcg2−/− mice after injury. These data suggest that Abcg2 function in nonmyogenic cells affects signaling that positively regulates myogenesis.

Results
Expression of Abcg2 increases upon muscle injury
Expression of Abcg2 has been previously reported in progenitor cells isolated from skeletal muscle (Meeson et al., 2004; Tanaka et al., 2009). To determine whether Abcg2 expression is dynamically regulated during muscle regeneration, we isolated mononuclear cells from the tibialis anterior (TA) muscle of mice injured with 1.2% BaCl2 at 2, 5, 12, and 30 d after injury as well as from uninjured TA muscles and analyzed the cells via flow cytometry for Abcg2 expression. We observed that in resting muscle, ~22% of mononuclear cells express Abcg2 (Fig. 1, A and F). The mean percentage of muscle cells expressing Abcg2 increases significantly between 2 and 5 d after injury from 20 to 39% of isolated cells (Fig. 1, B, C, and F). At 12 d after injury, the percentage of cells expressing Abcg2 begins to decline, reaching levels similar to those of uninjured tissue by 30 d after injury (Fig. 1, D–F). The increase in Abcg2-expressing cells at 5 d after injury is consistent with the reported increase seen in tissue sections after cardiotoxin-induced injury (Meeson et al., 2004). The dynamic change in the relative number of cells expressing Abcg2 coincides with the timing of both the inflammatory response and myoblast expansion.

Muscle regeneration is impaired in Abcg2−/− mice
Cells exhibiting the potential to generate myonuclei upon intramuscular transplantation have previously been identified in the muscle SP (Asakura et al., 2002; Tanaka et al., 2009). Additionally, Abcg2 is an important determinant of the SP phenotype, and muscle SP cells are lost in Abcg2-null (Abcg2−/−) mice (Zhou et al., 2001, 2002). These data together with the observation that Abcg2-positive cells increase significantly upon muscle injury suggest an important function for Abcg2 during muscle regeneration. Therefore, we tested the functional consequence of Abcg2 loss during skeletal muscle regeneration by assessing regeneration of the TA muscle after injury with 1.2% BaCl2. Before injury, we observed no significant histological defects in the TA muscle of Abcg2−/− mice (Fig. 2 A). Regeneration appears delayed in Abcg2−/− mice at 3 and 5 d after injury. Although Abcg2−/− mice appear to recover 12 d after injury, the persistence of small myofibers suggests that regeneration of new myofibers is still underway (Fig. 2 A). By 30 d after injury, the overall tissue architecture is restored, whereas the number of centrally nucleated myofibers, a hallmark of regeneration, as well as the total number of myonuclei in the TA muscle of Abcg2−/− mice is reduced compared with wild-type littermates (Fig. 2, B and C). On average, 60% of myofibers in Abcg2−/− injured muscles are centrally nucleated compared with 84% of centrally nucleated myofibers in injured muscles of wild-type mice. A significant number of smaller caliber myofibers remain, whereas large myofibers are lost in Abcg2−/− muscle (Fig. 2 D), as demonstrated by the a reduced mean myofiber cross-sectional area of 1,627 µm2 in Abcg2−/− TA muscles compared with 2,407 µm2 in wild-type TA muscles. Fewer centrally nucleated myofibers and smaller myofiber area in Abcg2−/− mice indicate impaired muscle regeneration.

To further understand the regeneration defects in Abcg2−/− mice, we assessed the expression of embryonic myosin heavy chain (MyHC; eMyHC) as an indicator of early myogenesis and the extent of BrdU uptake to indicate the proliferation status of cells at 5 d after BaCl2-induced injury. Fewer eMyHC-positive myofibers are present in Abcg2−/− muscle compared with wild-type muscle (Fig. 3 A). In Abcg2−/− mice, fewer cells have incorporated BrdU into their DNA (51 compared with 75 BrdU-positive cells per field), indicating that fewer cells are proliferating (Fig. 3, B–D). Interestingly, BrdU-positive nuclei found within laminin-positive regenerating myofibers (intra-laminar) compared with extralaminar BrdU-positive cells are more greatly reduced in Abcg2−/− muscle than wild-type muscle, indicating that proliferation of myogenic cells is more significantly affected than nonmyogenic cells (Fig. 3 D). This decrease in cycling myogenic cells is consistent with the decrease in the total number of myonuclei observed at 30 d after injury (Fig. 2 C). Furthermore, although the number of Pax7+ satellite cells found under the basal lamina is similar in uninjured mice, 30% fewer Pax7+ satellite cells are observed at 30 d after injury in the muscle of Abcg2−/− mice compared with wild-type mice (Fig. 3 E). The loss of Pax7+ cells at 30 d after injury suggests a decreased ability to replenish the satellite cell pool in Abcg2−/− mice.

A possible mechanism leading to the regeneration defects and loss of satellite cells we observe in Abcg2−/− muscle is an inherent defect in the ability of satellite cells to undergo myogenesis in response to injury. To test this possibility, we isolated satellite cells from the hind limbs of Abcg2−/− and wild-type littermate mice and assayed their myogenic potential in vitro. We observed no significant difference in clone size, number of Pax7− or MyoD-positive cells, or in the fusion index (Table I and Fig. S1). By 3 d in culture, 80% of myonuclei are MyoD positive, and ~40% are in multinucleated myotubes, which increases to nearly 70% after 5 d in culture.
CreERT2 fusion protein can be temporally controlled using systemically delivered tamoxifen. Adult Abcg2\textsuperscript{CreERT2}:R26R mice were treated with tamoxifen for a consecutive 3 d, and uninjured TA muscles were analyzed for expression of the β-galactosidase reporter protein at 6, 14, or 30 d after tamoxifen treatment.

β-galactosidase activity is detected in a small number of interstitial cell types at 6 d after treatment (Fig. 4, A and E). The number of labeled cells increases at 14 d and reaches a peak at \( \geq 30 \) d after tamoxifen treatment in uninjured muscle (Fig. 4, B, C, and E). In the TA muscle of untreated mice, no β-galactosidase activity was detected (Fig. 4 D). In uninjured muscle, we did not detect β-galactosidase staining in muscle fibers. Costaining for β-galactosidase and laminin on muscle sections showed that β-galactosidase–positive cells are excluded from the myofibers, confirming that interstitial cells are labeled by Abcg2 lineage tracing (Fig. 4 F). The increase in labeled cells over time after tamoxifen treatment suggests that Abcg2 labels a cell population in uninjured muscle that subsequently proliferates and contributes significantly to muscle interstitial cell types.

Because regeneration is impaired in Abcg2\textsuperscript{-/-} muscle after BaCl\textsubscript{2}-induced injury, and Abcg2 expression has been correlated with progenitor cells capable of forming myotubes

**Abcg2 labels interstitial cells in skeletal muscle**

Because we did not observe cell-autonomous defects in satellite cells, yet the percentage of Abcg2-expressing cells increases upon injury, we used genetic lineage tracing to identify cell progeny that arise from Abcg2-marked cells within skeletal muscle. To genetically lineage trace Abcg2-positive cells, we used a tamoxifen-inducible Cre-lox reporter system to label and follow the progeny of Abcg2-positive cells. A targeted knockin mouse expressing the Cre recombinase ER ligand binding domain fusion protein (CreERT2) from the Abcg2 locus was generated by inserting an internal ribosomal entry site–CreERT2 construct into the 3' untranslated region of the endogenous Abcg2 gene, resulting in expression of wild-type Abcg2 and the CreERT2 fusion gene (unpublished data). Abcg2\textsuperscript{CreERT2} mice were crossed with 129S-Gt(Rosa)26Sor\textsuperscript{tm1Sor}/J mice (referred to as R26R), which carry the LacZ reporter gene downstream of a loxP-flanked stop codon (Soriano, 1999). Activity of the CreERT2 fusion protein can be temporally controlled using systemically delivered tamoxifen. Adult Abcg2\textsuperscript{CreERT2}:R26R mice were treated with tamoxifen for a consecutive 3 d, and uninjured TA muscles were analyzed for expression of the β-galactosidase reporter protein at 6, 14, or 30 d after tamoxifen treatment. β-galactosidase activity is detected in a small number of interstitial cell types at 6 d after treatment (Fig. 4, A and E). The number of labeled cells increases at 14 d and reaches a peak at \( \geq 30 \) d after tamoxifen treatment in uninjured muscle (Fig. 4, B, C, and E). In the TA muscle of untreated mice, no β-galactosidase activity was detected (Fig. 4 D). In uninjured muscle, we did not detect β-galactosidase staining in muscle fibers. Costaining for β-galactosidase and laminin on muscle sections showed that β-galactosidase–positive cells are excluded from the myofibers, confirming that interstitial cells are labeled by Abcg2 lineage tracing (Fig. 4 F). The increase in labeled cells over time after tamoxifen treatment suggests that Abcg2 labels a cell population in uninjured muscle that subsequently proliferates and contributes significantly to muscle interstitial cell types.

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Figure 2. Regeneration is impaired in Abcg2−/− mice compared with wild-type mice. (A) Hematoxylin and eosin staining of uninjured TA muscles and TA muscles harvested at 3, 5, 12, and 30 d after injury. Hematoxylin and eosin-stained sections show delayed regeneration (day 3 and 5), fewer centrally nucleated myofibers (day 5 and 30), and reduced fiber size (day 12 and 30) in Abcg2−/− muscle. Bar, 50 µm. (B–D) Quantification of the reduced number of centrally nucleated myofibers (***, P < 0.001; B), reduced total myonuclei per fiber (**, P = 0.0019; C), and reduced myofiber area (D) at 30 d after injury are shown; mean cross-sectional area for wild-type (WT) myofibers is 2,407 µm² and Abcg2−/− myofibers is 1,627 µm² (P < 0.001). All values are means ± SEM. A minimum of 500 myofibers and three sections were analyzed for three mice per genotype. KO, knockout.
Figure 3. **Myogenesis and cell proliferation is disrupted in Abcg2-/- mice.** (A and B) Fewer eMyHC-expressing myofibers (green; A) and fewer BrdU-positive cells (green; B) are found in Abcg2-/- muscles at 5 d after injury compared with wild-type (WT) muscles. Bars, 50 µm. (C) Magnification of boxed regions in B. Bar, 10 µm. Nuclei are stained with DAPI. (D) The number of BrdU-positive cells per field is shown as means ± SEM for intralaminar (within laminin-positive regenerating myofibers; **, P < 0.01), extralaminar (P = 0.4), and total BrdU-positive cells (**, P < 0.01). n = 3 mice per genotype. (E) The number of Pax7-positive sublaminar cells per field is shown for uninjured (UI) and 30 d after injury TAs (***, P < 0.001 at 30 d postinjury [dpi]). Means ± SEM; n = 4 mice per genotype. KO, knockout.
number of regenerated myofibers (Fig. 5C and Fig. S2B). We observed clusters of 1–8 positive myofibers in the TA muscle of 5 out of 11 mice injured concurrently with tamoxifen treatment. The punctate staining pattern we observe is consistent with the cytoplasmic localization of the LacZ gene when low levels of LacZ are expressed from the Rosa locus and similar to the staining pattern observed in muscle fibers of ActinCreERT2;R26R mice upon low levels of Cre-mediated recombination (Fig. S2B). These results demonstrate that endogenous Abcg2-labeled cells can contribute to myofibers, but this contribution is minor in vivo using our injury/labeling procedure. Interestingly, Abcg2 marks ∼60% of interstitial cells regardless of whether the TA muscle was injured or when it was injured relative to tamoxifen treatment (Fig. 5E). Furthermore, when we bred Abcg2CreERT2;R26R to the mdx4cv mouse (mouse model of DMD), we reasoned that Abcg2 progeny would contribute to newly formed myofibers after injury. To test this hypothesis, we injured Abcg2CreERT2;R26R mice with 1.2% BaCl2 at various time points relative to tamoxifen injection and assessed the contribution of β-galactosidase–positive cells to regenerated myofibers at 30 d after injury. In the uninjured TA muscle 30 d after tamoxifen treatment, no β-galactosidase staining is detected in myofibers (Fig. 5A and Fig. 4C). Although an induced injury performed 14 d after tamoxifen treatment yielded no detectable β-galactosidase staining in regenerated (centrally nucleated) myofibers (Fig. 5B), an injury induced concurrently with tamoxifen treatment (at the time of the second tamoxifen injection) yielded detectable β-galactosidase activity in a small number of regeneraded myofibers (Fig. 5C and Fig. S2B). We observed clusters of 1–8 positive myofibers in the TA muscle of 5 out of 11 mice injured concurrently with tamoxifen treatment. The punctate staining pattern we observe is consistent with the cytoplasmic localization of the LacZ gene when low levels of LacZ are expressed from the Rosa locus and similar to the staining pattern observed in muscle fibers of ActinCreERT2;R26R mice upon low levels of Cre-mediated recombination (Fig. S2B). These results demonstrate that endogenous Abcg2-labeled cells can contribute to myofibers, but this contribution is minor in vivo using our injury/labeling procedure. Interestingly, Abcg2 marks ∼60% of interstitial cells regardless of whether the TA muscle was injured or when it was injured relative to tamoxifen treatment (Fig. 5E). Furthermore, when we bred Abcg2CreERT2;R26R to the mdx4cv mouse (mouse model of DMD)......

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The number of nuclei in multinucleated MyHC-positive myotubes per total myonuclei was scored (fusion index). Values are means ± SEM. n = 3 independent experiments.

Table 1: Abcg2−/− satellite cells exhibit no cell-autonomous defects

Figure 4. Interstitial cell types are labeled by an Abcg2-driven CreERT2 and increase over time. [A–C] X-gal staining of uninjured TA muscles at 6 d (A), 14 d (B), and 30 d (C) after tamoxifen treatment show labeling of interstitial cells that increase over time. (D) TA muscle sections from untreated mice show no detectable X-gal staining. (A′–C′) Magnification of A–C (A′–C′) and quantification of β-galactosidase (β-gal)–positive cells (E) are shown. Means ± SEM; n = 3 mice per time point. (F) Immunoreactivity of β-galactosidase and laminin antibodies confirms that labeled cells are excluded from the myofiber. Nuclei are stained with DAPI (blue). Arrowheads indicate β-galactosidase–positive cells. Bars, 50 µm.
Because Abcg2-marked cells predominately contribute to interstitial cells, and satellite cell–derived cultures from Abcg2−/− mice display no detectable defects, yet regeneration is impaired in Abcg2−/− mice, we hypothesized that Abcg2-marked interstitial cells indirectly support myogenesis. To better understand which cell types are labeled by Abcg2, we undertook a thorough analysis of the cells marked by Abcg2 lineage tracing in uninjured muscle. Our previous analysis indicated that many cells coexpress Abcg2 and Sca-1 (stem cell antigen 1), so we assessed the expression of Sca-1 within Abcg2-labeled progeny. Sca-1 is widely expressed by progenitor populations in multiple tissues and many muscle interstitial cell types, including FAPs and CD31-positive endothelial cells (Tamaki et al., 2002; Mitchell et al., 2005; Joe et al., 2010). By immunofluorescence using anti-β-galactosidase antibodies, β-galactosidase is widely colocalized in cells expressing Sca-1 (Fig. 6 A) as Duchenne muscular dystrophy; Im et al., 1996), we did not detect contribution from Abcg2-labeled cells to myofibers in the mdx4cv mouse (Fig. 5 D), suggesting Abcg2-labeled cells do not contribute directly to muscle regeneration in a model of chronic muscle damage.

### Abcg2 progeny include multiple interstitial cell types

Cells located in the interstitium include several cell types that either possess myogenic potential or indirectly and positively regulate myogenesis (Péault et al., 2007; Abou-Khalil et al., 2010). Among these cells are vascular-associated cells, including endothelial cells and pericytes, FAPs, muscle SP cells, and PW1+/Pax7− interstitial cells (Asakura et al., 2002; Tamaki et al., 2002; Meeson et al., 2004; Dellavalle et al., 2007; Joe et al., 2010; Mitchell et al., 2010; Uezumi et al., 2010).
progenitors and FAPs found in muscles have been reported (Joe et al., 2010; Uezumi et al., 2010). We determined that although the majority of FDG-positive and CD45 and CD31 double-negative cells express PDGF-R-α, few are also positive for Sca-1, indicating that <1% of total FDG-positive cells are FAPs (Fig. 7 E and Table II).

Abcg2 is expressed by stem cells in bone marrow as well as skeletal muscle (Zhou et al., 2001), and bone marrow cells positive for CD45 (a hematopoietic cell lineage marker) have been shown to traffic to skeletal muscle (Rivier et al., 2004). Therefore, we determined whether Abcg2 progeny were CD45 positive and observed that <10% of FDG-positive cells are also positive for CD45 in uninjured muscle (Fig. 7 F and Table II). Within the FDG-positive, CD45-negative fraction of cells, ~20% are Sca1 and CD34 double positive. It remains unclear what this small fraction of cells exactly is, as expression of Sca-1 and CD34 has been associated with numerous progenitor populations, including muscle SP cells, muscle-derived stem cells, and myoendothelial cells (Tamaki et al., 2002; Péault et al., 2007). Together, these data suggest

To quantify this coexpression, we took advantage of the fluorescent β-galactosidase substrate fluorescein di-β-d-galactopyranoside (FDG) to label Abcg2 progeny for analysis by flow cytometry. At 2 wk or longer after tamoxifen treatment, ~25% of mononuclear cells from uninjured hind-limb muscles are FDG positive (Fig. 7 A). In uninjured muscle, CD31-positive endothelial cells comprise >80% of FDG-positive cells (Fig. 7 B and Table II). The majority of these cells are also positive for the cell surface markers Sca-1 and α7-integrin (Fig. 7 C). We further considered the minority of FDG-positive cells that are negative for CD31 (Fig. 7 B). Myogenic cells have been characterized as α7-integrin positive and/or CD34 positive within the CD31-negative and Sca-1–negative fraction (Montarras et al., 2005; Sacco et al., 2008; Joe et al., 2010). Based on this combination, <1% of FDG-positive cells are myogenic progenitors (Fig. 7, D and F; and Table II). Recently, adipogenic progenitors and FAPs found in muscles have been reported (Joe et al., 2010; Uezumi et al., 2010). We determined that although the majority of FDG-positive and CD45 and CD31 double-negative cells express PDGF-R-α, few are also positive for Sca-1, indicating that <1% of total FDG-positive cells are FAPs (Fig. 7 E and Table II).

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Figure 7. β-galactosidase–positive cells coexpress markers of muscle interstitial cell types. FDG was used to label live cells expressing β-galactosidase isolated from hind-limb muscles followed by staining with fluorophore-conjugated antibodies for analysis by flow cytometry including Sca-1, CD31, α7-integrin, CD45, CD34, and PDGF-Rα. (A) Approximately 25% of cells detected from Abcg2^{CreERT2};R26R mice treated with tamoxifen are FDG+ (A, gated region). Less than 1% of cells isolated from mice that had not received tamoxifen are FDG+ (gated region) similar to unlabeled cells. Analysis of FDG coexpression with various markers was performed by first gating for FDG and then the antibody of interest and are shown as described at the bottom. Gates are set to <1% positives on appropriate fluorescence minus one controls. (B) The majority of FDG+ cells are positive for the endothelial cell marker CD31 (blue box). (C) FDG+ and CD31+ (blue box in B) cells are gated onto a plot for α7-integrin versus Sca-1, showing that most CD31+ cells are also α7-integrin+ and Sca-1+ (C, top right quadrant). (B and D) Similarly, FDG+ and CD31− (11%, red box in B) cells are gated onto a plot for α7-integrin versus Sca-1 showing 10% myogenic (α7-integrin+ and Sca-1−) cells (red box in D), indicating <1% of FDG+ cells are myogenic. (E) The CD45/CD31− (7%, red box) fraction of FDG+ cells was gated onto a plot for PDGF-Rα versus Sca-1, which shows most of these cells are PDGF-Rα+ and Sca-1−. (F) CD45+ cells make up <10% of FDG+ cells (blue box). The FDG+ and CD45− fraction (red box) is gated for CD34 versus Sca-1, which shows that ~20% are CD34+ and Sca-1+ and may include other progenitor populations but few myogenic cells (CD34+ and Sca-1−). Dot plots shown are representative of three to six independent experiments. APC, allophycocyanin; PE, phycoerythrin.
that most Abcg2 progeny are resident endothelial cells within muscle, and a small number of Abcg2 progeny are derived from the hematopoietic lineage.

**Abcg2-labeled, CD45-positive cells increase upon injury**

Because Abcg2-expressing cells increase upon an induced muscle injury, we further extended our study of Abcg2-labeled cells to 5 d after muscle injury to understand which cell types may be positively regulating muscle regeneration. Similar to the profiles obtained using the anti-Abcg2 antibody (Fig. 1), the percentage of mononuclear cells that are FDG positive increases at 5 d after injury and subsequently, returns to uninjured levels by 30 d after injury (Fig. 8A). This significant increase in Abcg2-labeled progeny could represent the proliferation of cells labeled in uninjured tissue, or it could represent an influx of cells from the peripheral blood in response to injury. To test these two possibilities, Abcg2-marked cells were labeled with FDG and costained for antibodies of interest at 5 d after muscle injury and then analyzed by flow cytometry. Compared with uninjured TA muscles, the relative percentage of CD31- and Sca-1-positive endothelial cells within FDG-positive cells decreased in injured muscle (Fig. 8B). However, the majority of FDG-positive cells at 5 d after injury were immunoreactive for CD45 and negative for Sca-1 (Fig. 8C). CD45 and Sca-1 double-positive resident muscle cells increase upon injury (Polesskaya et al., 2003), whereas bone marrow–derived CD45-positive cells have been shown to traffic to skeletal muscle after injury (Rivier et al., 2004). We hypothesized that the influx of FDG and CD45 double-positive cells upon injury are derived from a lineage originating in the bone marrow not a resident muscle lineage, as they are negative for Sca-1. Because the inflammatory response precedes and supports myogenesis, we reasoned that some of the Abcg2-labeled, bone marrow–derived cells may be macrophages (Arnold et al., 2007; Tidball and Wehling-Henricks, 2007; Tidball and Villalta, 2010). Thus, we asked whether the muscle injury-induced, Abcg2-labeled cells included macrophages. At 5 d after injury, we detected coexpression by immunofluorescence of the Abcg2-responsive reporter gene β-galactosidase and the macrophage marker F4/80 (Fig. 8D). Therefore, the transient increase in Abcg2-labeled cells in injured muscle tissue likely derives from circulating hematopoietic cells. Collectively, our data suggest that Abcg2-marked cells in muscle include a population of resident interstitial cells (CD45 negative in uninjured tissue) and a population of circulating cells that traffic to the muscle upon injury (CD45 positive), further supporting the hypothesis that Abcg2-positive cells positively contribute to muscle regeneration.

**Immune response, but not angiogenesis, is affected in Abcg2<sup>–/–</sup> mice upon injury**

The impaired regeneration phenotype in Abcg2<sup>–/–</sup> mice is not explained by cell-autonomous defects in satellite cells; however, Abcg2 is expressed in muscle interstitial cells types in uninjured tissue and infiltrates cells upon injury. It is becoming appreciated that the cellular processes of angiogenesis and the inflammatory response precede myogenesis. Both of these cellular events positively regulate myogenesis (Abou-Khalil et al., 2010; Tidball and Villalta, 2010). Therefore, we examined the angiogenic and immune responses at early time points after injury in Abcg2<sup>–/–</sup> muscle. The density of vasculature as assessed by CD31 and vascular endothelial (VE) cadherin staining was unaffected in Abcg2<sup>–/–</sup> muscle at 5 d after injury (Fig. 9, C–G). Although there appears to be no significant defect in generation of new vasculature, signaling from endothelial cells could be impaired, so we analyzed the mRNA expression levels of several angiogenic signaling genes. We detect no differences in uninjured muscle. At 3 d after injury, VEGFα and HIF2α remain unchanged, whereas Angiopoietin-1, Angiopoietin-2, and HIF1α trend toward decreased expression in Abcg2<sup>–/–</sup> muscle (Fig. 9, C–G).

Impaired recruitment of macrophages to muscle after injury can have a negative effect on muscle regeneration (Arnold et al., 2007; Contreras-Shannon et al., 2007). The significant increase in Abcg2 expression correlates with recruitment of bone marrow–derived cells, so we determined whether the immune response to muscle injury was impacted in Abcg2<sup>–/–</sup> muscle. The inflammatory response is characterized by two waves of macrophage infiltration: M1 macrophages

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**Table II. Abcg2-labeled cell populations in uninjured skeletal muscle**

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<td>Other muscle progenitor cells&lt;sup&gt;de&lt;/sup&gt;</td>
<td>CD45&lt;sup&gt;−&lt;/sup&gt;, Sca1&lt;sup&gt;+&lt;/sup&gt;, CD34&lt;sup&gt;+&lt;/sup&gt;</td>
<td>&lt;20</td>
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Values are means ± SEM; n = 3–6 independent experiments.

<sup>a</sup>Blanco-Bose et al., 2001.

<sup>b</sup>Joe et al., 2010.

<sup>c</sup>Uezumi et al., 2010.

<sup>d</sup>Tamaki et al., 2002.

<sup>e</sup>Péault et al., 2007.
Macrophages may be negatively impacted in Abcg2−/− muscle. Consistent with this observation, we find that expression of TNF-α and IL-6, both proinflammatory cytokines that inhibit M2 macrophage recruitment (Zádor et al., 2001; Warren et al., 2002), trend toward increased expression in Abcg2−/− muscle (Fig. 10, D and E). Additionally, CCL2 (MCP-1), a chemotactic and activating factor for macrophages that has been shown to be important for muscle regeneration (Shireman et al., 2007), trends toward decreased expression in Abcg2−/− muscle (Fig. 10 F).

Figure 8. Abcg2-labeled cells that are CD45 positive increase at 5 d after BaCl2-induced injury. Cells labeled with FDG were analyzed via flow cytometry. (A) Representative dot plots show FDG versus side scatter for cells isolated from injured TA muscles at 5 and 30 d postinjury (dpi) and the respective contralateral uninjured TA muscles. Gated regions indicate the percentage of FDG+ cells. (B and C) FDG+ cells from uninjured (left) and 5 d after injury TA muscles (right) were gated for CD31 versus Sca-1 (B) and CD45 versus Sca-1 (C). As a fraction of the FDG-labeled cells, endothelial cells decrease (CD31+ and Sca-1−; top right quadrant in B) and CD45+ (Sca-1−; bottom right quadrant in C) bone marrow-derived cells increase at 5 d after injury relative to uninjured control. Dot plots shown are representative of four experiments. Numbers correspond to the percentage of positive cells in the given quadrant. (D) Tissue sections from 5 d after injury TA muscle were stained for β-galactosidase (β-gal) and the macrophage marker F4/80. Arrows indicate cells that coexpress β-galactosidase and F4/80 (yellow). APC, allophyrocyanin; PE, phycoerythrin. Bars, 50 µm.
endothelial cells and pericytes in uninjured tissue. Furthermore, upon muscle injury, Abcg2-expressing cells increase, and Abcg2 progeny include infiltrating cells from the peripheral blood, of which some are macrophages. The recruitment of circulating cells to muscle after injury is impaired in Abcg2−/− mice. Abcg2 labeling gives rise to vascular-associated cells within skeletal muscle based on the conditional expression of the LacZ reporter gene, we show that Abcg2-marked cells generate numerous interstitial cell types, including endothelial cells and pericytes in uninjured tissue. Furthermore, upon muscle injury, Abcg2-expressing cells increase, and Abcg2 progeny include infiltrating cells from the peripheral blood, of which some are macrophages. The recruitment of circulating cells to muscle after injury is impaired in Abcg2−/− mice.

Discussion

Expression of the ABC transporter Abcg2 is the major molecular determinant of the SP phenotype in skeletal muscle and in other cells, including cells in the hematopoietic lineage and heart tissue (Zhou et al., 2002; Martin et al., 2004; Meeson et al., 2004). In this study, we demonstrate that upon genetic loss of Abcg2, in which SP cells are depleted, skeletal muscle regeneration is delayed. We further show that in skeletal muscle, Abcg2-marked cells give rise to multiple interstitial cell types, including...
Sca-1 (CD45 negative), which likely includes SP cells and possibly other muscle-derived stem cells or myoendothelial cells (Tamaki et al., 2002; Zheng et al., 2007; Péault et al., 2007). Upon injury, we observe a significant increase in the percentage of Abcg2-labeled cells. Unlike in uninjured tissue in which the majority of labeled cells are CD45 negative, upon injury, the majority of Abcg2 progeny are CD45 positive. Furthermore, a subset of Abcg2 progeny is positive for the macrophage marker F4/80. Upon injury, bone marrow–derived cells, including circulating monocytes, which differentiate into macrophages, are recruited to the muscle where they participate in the inflammatory process and promote regeneration (Rivier et al., 2004; Arnold et al., 2007). Hematopoietic lineage progenitors also express Abcg2; therefore, it is possible that the observed increase in Abcg2-positive cells upon injury results from circulating cells infiltrating the muscle tissue. In support of this hypothesis, circulating cells derived from hematopoietic stem cells are labeled by Abcg2. Using a conditional Rosa26-YFP reporter, YFP is detected in circulating cells expressing GR1 and Mac1, surface antigens of monocytes (unpublished data).

Figure 10. The antiinflammatory immune response is disrupted in Abcg2−/− mice. (A and B) Staining with the macrophage marker F4/80 with and without laminin is shown for tissue sections 3 d (A) and 5 d (B) after BaCl2-induced injury. Bars, 50 μm. (C) Sections were scored for F4/80-positive cells. Values shown are means ± SEM; P < 0.01 for 5 d postinjury (dpi); n = 3 mice per genotype for each time point. (D–F) Quantitative RT-PCR for TNF-α (D), IL-6 (E), and CCL2 (F) was performed on RNA isolated from uninjured (UI) TA and 3 d after injury TA muscles (n = 3). WT, wild type; KO, knockout.
Based on these observations, we propose that Abcg2 labels two distinct populations of cells: (1) resident muscle interstitial cells and (2) circulating progenitor cells that traffic to skeletal muscle upon injury.

**Abcg2+ cells are not a significant source of myogenic progenitors**

Previous studies have proposed that SP cells prospectively isolated from skeletal muscle possess myogenic activity and thus, may either contribute to renewal of the satellite cell population or may be an independent progenitor cell (Asakura et al., 2002; Tanaka et al., 2009). Our lineage tracing data using the Abcg2 locus to drive expression of CreERT2 suggests that Abcg2-labeled cells possess limited myogenic activity. A few possibilities may account for the low contribution of Abcg2 labeling to new myofibers in our study. (a) Prior studies demonstrated the ability of isolated SP cells to contribute to generation of new myofibers upon intramuscular transplantation (Asakura et al., 2002; Meeson et al., 2004). The manipulation of isolated cells for transplantation may alter the properties of SP cells such that they can undergo myogenic differentiation. Alternatively, the transplant procedure could give the SP cells a competitive advantage over endogenous satellite cells. (b) The Abcg2-labeled cells that contribute to myofibers may come from bone marrow cells. Previous studies have shown that bone marrow–derived cells, including SP cells, differentiate to myogenic cells at a low frequency (Ferrari et al., 1998; Gussoni et al., 1999; Ojima et al., 2004; Luth et al., 2008). These observations are consistent with the low Abcg2 labeling of regenerated myofibers we detect when injuries are performed concurrently with tamoxifen treatment such that the Abcg2 and CD45 double-positive cells are also labeled. (c) The level of CreERT2 expression from the Abcg2 locus in SP cells may be below the threshold required for efficient Cre-mediated recombination. In hematopoietic stem cells, detection of the conditional Rosa26-YFP reporter is low (unpublished data) despite the firmly established expression of Abcg2 in hematopoietic stem cells (Zhou et al., 2001, 2002).

**Loss of Abcg2 results in impaired muscle regeneration**

In an injury-induced model of muscle regeneration, genetic loss of Abcg2 leads to reduced myogenic proliferation and reduced numbers of myofibers expressing eMyHC. This phenotype is consistent with a loss of total myonuclei, reduced centrally nucleated myofibers, and reduced myofiber size as well as a loss of Pax7+ satellite cells at 30 d after injury. Although the impaired regeneration phenotype in Abcg2−/− mice is not as severe as other models of impaired skeletal muscle regeneration in which both the immune response and angiogenesis are impaired, such as the CCR2-null mice (Contreras-Shannon et al., 2007; Ochoa et al., 2007), it is reminiscent of the resulting impaired muscle regeneration upon partial depletion of monocytes and macrophages (Arnold et al., 2007) or loss of CCL2 (MCP-1; Martinez et al., 2010). Consistent with partial depletion of macrophages, we observe a specific effect on recruitment of antiinflammatory (M2) macrophages. Inhibition of macrophages at day 4 (muscle-loading model) leads to impaired muscle regeneration as measured by central nucleation and impaired satellite cell differentiation (Tidball and Wehling-Henricks, 2007).

In addition, there may be functional compensation from other ABC transporters. Functional compensation by ABC transporters is known to occur; for example, Abcg2 can compensate for loss of mdrla/1b in hematopoietic stem cells (Zhou et al., 2001). Both mdrla/1b are expressed in mouse skeletal muscles and could provide compensation for Abcg2 loss in some circumstances (Croop et al., 1989; Israeli et al., 2004).

Impaired skeletal muscle regeneration in Abcg2−/− mice is consistent with a previously identified role for Abcg2 in tissue defense and organ regeneration. In hematopoietic stem cells and cardiac progenitor cells, Abcg2 provides an important cell survival advantage under hypoxic conditions (Krishnamurthy et al., 2004; Martin et al., 2008). Moreover, a recent study demonstrated that Abcg2 has a critical function in cardiac repair after myocardial infarction; specifically, impaired survival of microvascular endothelial cells lead to cardiac rupture in Abcg2−/− mice (Higashikuni et al., 2010). Unlike this myocardial infarction model, the microvasculature appears to be unaffected after injury of skeletal muscle with BaCl2. However, the myocardial infarction model is a more severe injury, and the roles of Abcg2 may be slightly different in the heart and skeletal muscle. Nonetheless, it is likely that Abcg2 provides a critical cell survival function, either through its ability to export genotoxic substrates from the cell or through an unknown novel mechanism in which the ABC transporter affects signaling between cells. This is an attractive hypothesis because cell-autonomous defects in satellite cells from Abcg2−/− mice do not appear to account for the defects observed during regeneration in vivo. Moreover, cells derived from Abcg2-marked cells, including endothelial cells and macrophages, are known to positively regulate myogenesis, and we observe defects in the macrophage response. Additionally, endothelial cells stimulate growth of satellite cells through the secretion of a variety of growth factors, including IGF-1, VEGF, FGF-2, PDGF-BB, and hepatocyte growth factor (Christov et al., 2007). Consistently, we observe modest decreases in angiogenic factors, including HIF1-α, and the angiopoietin genes that can contribute to disrupted signaling during regeneration. The immune response is critical to healthy muscle regeneration, and macrophages have been shown to enhance satellite cell growth and protect satellite cells from apoptosis (Chazaud et al., 2003; Sonnet et al., 2006). The inflammatory response to muscle injury is complex, involving two distinct waves of macrophage infiltration, both proinflammatory and antiinflammatory, that secrete cytokines with differing effects on myogenesis and muscle regeneration (Tidball and Villalta, 2010). Interestingly, the proinflammatory cytokines TNF-α and IL-6 are increased, and the chemotactic and activating cytokine CCL-2, which has been previously shown to affect muscle regeneration (Zádor et al., 2001; Warren et al., 2005; Shirer et al., 2007; Martinez et al., 2010), is decreased in Abcg2−/− muscle. The specific effect of loss of Abcg2 on the antiinflammatory phase of the immune response correlates with the peak in Abcg2.
expression at 5 d after injury. Together, these data suggest a role for Abcg2 during muscle regeneration in which it affects signaling between inflammatory and myogenic cells.

Although the mechanism of Abcg2 function remains to be uncovered, here, we demonstrate a physiologically significant function for Abcg2 in regeneration of skeletal muscle. These data highlight the involvement of Abcg2 in a complex biological process involving organ regeneration. Furthermore, these findings contribute to the emerging consensus of muscle healing as a system in which nonmyogenic cells, namely endothelial cells, immune cells, and others, play a critical role in skeletal muscle regeneration.

Materials and methods

Mice

Mice were housed and bred according to National Institutes of Health guidelines for the ethical treatment of animals in a pathogen-free facility. All procedures and protocols were approved by the Institutional Animal Care and Use Committee at the University of Colorado. Abcg2CreERT2 (unpublished data) crossed to the conditional Rosa26-LacZ reporter, Abcg2 knockout mice (Zhou et al., 2002), and mdx mice. For injury of the TA muscle, mice were anesthetized, and the right TA muscle was digested with type I collagenase (Worthington) for 1 h at 37°C, filtered, and recovered in F12-C with 15% horse serum and 0.5 nM FGF-2. For antibody labeling, mice were incubated for 45 min at 4°C with mouse Abcg2 [Bcrp1, clone 5D3; BD] at 1:100 followed by anti-mouse IgG–PE-Cy5 (Santa Cruz Biotechnology, Inc.) secondary antibody. For FDG (Invitrogen) labeling, an equal volume of cells and 2 mM FDG was mixed and incubated at 37°C for 1 h. 10 vol cold media was added, and cells were recovered on ice for 1 h. Cells were then incubated with the following antibodies at 4°C for 30 min: rat anti–Sca-1–PE conjugated (BD) at 1:200, rat anti–CD34–Alexa Fluor 647 (BD) at 1:1,000, rat anti–CD34–Alexa Fluor 647 (BD) conjugated at 1:100, and rat anti–PDGF-R-α–allophycocyanin conjugated (eBioscience) at 1:100. DAPI was added at 1 µg/ml to exclude dead cells. Cell analysis was performed with an ADP three-laser flow cytometer (CyAn; Beckman Coulter). Appropriate fluorescence minus one controls were used to set gates to <1% background. Data were analyzed after sort with FlowJo software (Tree Star).

RNA isolation and quantitative RT-PCR

TA muscles 3 d after BaCl2-induced injury and uninjured contralateral control from wild-type and Abcg2−/− mice were harvested and homogenized, and RNA was isolated using a purification kit (RNeasy; Invitrogen). cDNA was made using reverse transcriptase (Superscript III; Invitrogen) with random hexamer primers, and quantitative PCR was performed using SYBR green (Applied Biosystems) and gene specific primers as previously published (Higashikuni et al., 2010).

Microscopy, image processing, and figure preparation

Brightfield images were acquired with a microscope (DM5500; Leica) using Metamorph software (Molecular Devices), coupled with a camera (DFC; Leica). Objectives used were HC Plan Apochromat 20×/NA 0.70–0.75 (Nikon). Fluorescent micrographs were taken with a confocal microscope (LSM 5; Carl Zeiss) using ZEN 2009 software (Carl Zeiss) or with an epifluorescence microscope (Eclipse E800; Nikon) using SlideBook v4.1 acquisition software coupled to a digital camera (Sensicam; Cooke). Lenses used with the confocal microscope were Plan Apochromat 63× oil/NA 1.4 differential interference contrast M27 (Carl Zeiss). Lenses used with the epifluorescence microscope were Plan Fluor either 40×/NA 0.75 differential interference contrast M or 20×/NA 0.50 Ph1 DDL (Nikon). All digital microscopic images were acquired at room temperature. Mounting medium (Vectashield) was used for imaging. The fluorochromes used were Alexa Fluor 488 and Alexa Fluor 594 or Alexa Fluor 555 (confocal) conjugated to secondary antibodies for immunofluorescence as indicated in the Immunofluorescence section. For figure preparation, images were exported in Photoshop (Adobe), if necessary, brightness and contrast were adjusted for the entire image, the image was cropped, and individual color channels were extracted (when required) without color correction or γ adjustments.

Statistical analysis

All data are presented as means ± SEM. Student’s t test (unpaired and two tailed) was used to determine the statistical significance of individual data sets in Prism (version 5; GraphPad Software). Differences are considered significant for P < 0.05, very significant for P < 0.01, and highly significant for P < 0.001.
Online supplemental material
Fig. S1 shows that Abcg2-/- satellite cells differentiate normally when isolated and cultured and is related to Table I. Fig. S2 shows punctate staining of X-gal in muscle sections isolated from tamoxifen-treated ActinCreERT2;R26R and Abcg2CreERT2;R26R and is related to Fig. S5. Online supplemental material is available at ftp://www.jcb.org/cgi/content/full/jcb.201103159/DC1.

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References


Figure S1. **Satellite cell cultures from Abcg2−/− mice show no defects.** Primary cells were isolated from hind-limb muscles of wild-type and Abcg2−/− cells, preplated overnight, and cultured for 3–5 d. (A) Primary cells harvested after 3 d in culture were stained with Pax7 and MyoD. Bar, 50 µm. (B and C) Cells cultured for 3 d (B) or 5 d (C) were stained with myosin heavy chain (MyHC). Bar, 100 µm. n = 3 independent experiments.
Figure S2. Punctate X-gal staining is detected in myofibers of ActinCreERT2;R26R mice. (A and B) X-gal staining of tissue sections from ActinCreERT2;R26R uninjured TA muscle 30 d after tamoxifen treatment (A) and from Abcg2CreERT2;R26R 30 d postinjury (dpi) TA muscle injured during tamoxifen treatment (B). Arrows indicate two fibers with punctate β-galactosidase staining. Bar, 50 µm.