Degeneration, Regeneration, and Cicatrization after Fat Grafting: Dynamic Total Tissue Remodeling during the First 3 Months

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Background: Fat grafting is promising, but clinical outcomes are not always predictable. The mechanisms of tissue revascularization/regeneration, and tissue necrosis and subsequent absorption/fibrosis of the graft, are poorly understood.
Methods: An autologous inguinal fat pad was transplanted under the scalp of mice, and detailed cellular events during the first 3 months were investigated with immunohistochemistry.
Results: Except for the most superficial surviving zone, death of all adipocytes was confirmed at 1 week. Perilipin-positive small new adipocytes appeared at 1 week and peaked in number at 4 weeks in the regenerating zone (the second zone). In the most central necrotizing zone, adipogenesis did not occur and many inflammatory cells were observed after 2 weeks. $CD34^+/Ki67^+$ proliferating adipose stem/progenitor cells were seen at 1 to 4 weeks, but the majority of proliferating cells were $MAC2^+$ monocytes/macrophages. Although $CD206^-$ M1 macrophages surrounded oil droplets for phagocytosis, $CD206^+$ M2 macrophages appeared in areas where adipocyte replacement failed and formed multiple layers for cicatrization of oil drop spaces. Adipogenesis was complete by 12 weeks, but stabilization of nonregenerated areas was still ongoing at that time. Lipid droplets derived from dead adipocytes were absorbed slowly and thus aided adipose remodeling by maintaining the space until adipocyte regeneration.
Conclusions: Dynamic remodeling after fat grafting was confirmed. Adipocyte fate differed, depending on the microenvironment: intact survival, replacement with a new adipocyte, or replacement with cicatrization/oil cyst. This detailed understanding will help refine surgical grafting procedures and postoperative evaluation. (*Plast. Reconstr. Surg.* 133: 00, 2014.)

Adipose tissue has been widely used as an injectable substance and has been recently reevaluated as a tool for not only augmenting tissue volume (volumization) but also for enhancing tissue potential (revitalization) and modulating immunoreaction (harmonization). Fat grafting has several potential drawbacks, including clinical unpredictability, and thus efforts have focused on seeking ways to achieve improved and more consistent final retention.[1–4] The variability of clinical results originates partly from unique characteristics of adipose tissue; therefore, further research is required to explore the underlying cellular and molecular mechanisms in the healing and remodeling process after fat grafting. It is important to understand not only how the graft is retained, but also how long-term tissue atrophy, oil cyst formation, and progressive calcification occur.

A variety of cell types are present in subcutaneous adipose tissue,[5] and adipocytes account for only 20 percent or less of the total number of cells.[6] We previously reported cellular events during various types of adipose tissue remodeling, such as those seen after surgically induced ischemia,[7] ischemia-reperfusion injury,[8] and fat grafting.[9] In those studies, adipose stem/progenitor/ AQ1

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stromal cells were demonstrated to play pivotal roles in adipose tissue repair and regeneration, whereas inflammatory cells, such as infiltrated macrophages, contributed to removing degenerated components. A series of primary and subsequent signals, including hypoxia and cytokines, appear to regulate the complex events during adipose tissue remodeling.[10–14]

We recently presented convincing evidence that most adipocytes (except for those located superficially) die as early as day 1 after fat grafting, and the subsequent regeneration process starts as early as day 5.[9] Adipose stem/progenitor/stromal cells can stay alive for up to 3 days, even under stressful conditions, such as severe hypoxia. Immunohistologic staining for perilipin[15] was the primary technology used to distinguish living from dead adipocytes and verify dynamic adipocyte replacement in the grafted fat tissue.

The present study was designed to clarify the detailed cellular events involved in the remodeling process after microfat grafting and describe the long-term fate of adipose tissue and adipocytes. Understanding these events should help establish novel technologies to maximize and stabilize long-term results. In addition to the fragile nature of adipose tissue, a number of patient-derived or surgeon-dependent factors appear to affect clinical outcomes. We need to clarify how these affect not only tissue revascularization/regeneration but also tissue necrosis and the subsequent absorption/fibrosis of the microfat graft.

MATERIALS AND METHODS

Animal Models for Autologous Fat Grafting

Animals were cared for in accordance with our institutional guidelines. Eight-week-old BL6/Jjcl mice were purchased from Japan CLEA, Inc. (Tokyo, Japan). The mice were anesthetized with pentobarbital (50 mg/kg). The inguinal skin was incised and the subcutaneous inguinal fat pad (150 to 200 mg) was gently dissected and harvested. The fat pad was small, similar to the size of aspirated fat tissue used for clinical fat injection in humans. The fat pad was inserted through a 5-mm-long skin incision into a small pocket made under the scalp of the same mouse, followed by skin closure with a 7-0 nylon suture. The fat grafting was performed in 30 mice, which were killed after 0 (sham operation), 1, 2, 4, 8, or 12 weeks ($n = 5$ at each time point). After the scalp was incised, the grafted fat sample was harvested by careful removal from surrounding tissue and then weighed. The normalized sample weight ratio, which is the ratio of the harvested sample weight to the body weight, was used to evaluate the change in sample weight. Each harvested sample was fixed (Zinc Fixative; BD Biosciences, San Jose, Calif.) and embedded in paraffin for histologic assessment.

Histologic Assessment

After preparing 5-μm-thick sections of the harvested tissue samples, we performed immunostaining with the following primary antibodies: guinea pig anti-mouse perilipin (dilution, 1:200; Progen, Heidelberg, Germany), rat anti-mouse MAC-2 (dilution, 1:200; Cedarlane Corp., Burlington, Ontario, Canada), goat anti-mouse CD34 (dilution, 1:100; Santa Cruz Biotechnology, Santa Cruz, Calif.), rabbit anti-human Ki67 (clone SP6; dilution, 1:200; Thermo Fisher Scientific, Fremont, Calif.), and rabbit anti-mouse CD206 (dilution, 1:100; Santa Cruz Biotechnology). For double fluorescence staining, the following secondary antibodies were used: Alexa Fluor 488–conjugated goat anti-guinea pig immunoglobulin G (dilution, 1:200; Invitrogen, Carlsbad, Calif.), Alexa Fluor 568–conjugated donkey anti-rat immunoglobulin G (dilution, 1:200; Invitrogen), Alexa Fluor 488–conjugated donkey anti-goat immunoglobulin G (dilution, 1:200; Invitrogen), Alexa Fluor 594–conjugated donkey anti-rabbit immunoglobulin G (dilution, 1:200; Invitrogen), and Alexa Fluor 488–conjugated goat anti-rabbit immunoglobulin G (dilution, 1:200; Invitrogen). An isotype immunoglobulin G was used as a negative control for each immunostaining. Nuclei were stained with Hoechst 33342 (dilution, 1:200; Dojindo, Tokyo, Japan) and blood vessels were stained with isolectin 488 (dilution, 1:200; Invitrogen). The number of small adipocytes (perilipin-positive cells with a diameter <20 μm) was counted in at least four field images for each sample.

Statistical Analysis

The results are expressed as mean ± SEM. The Welch t test was used for all comparisons. Values of $p < 0.05$ were considered statistically significant.

RESULTS

Macroscopic and Weight Changes of Grafted Tissue Samples

The size and weight of the grafted fat tissue decreased over time (Fig. 1). [**See Figure, Supplemental Digital Content 1**, which shows F1

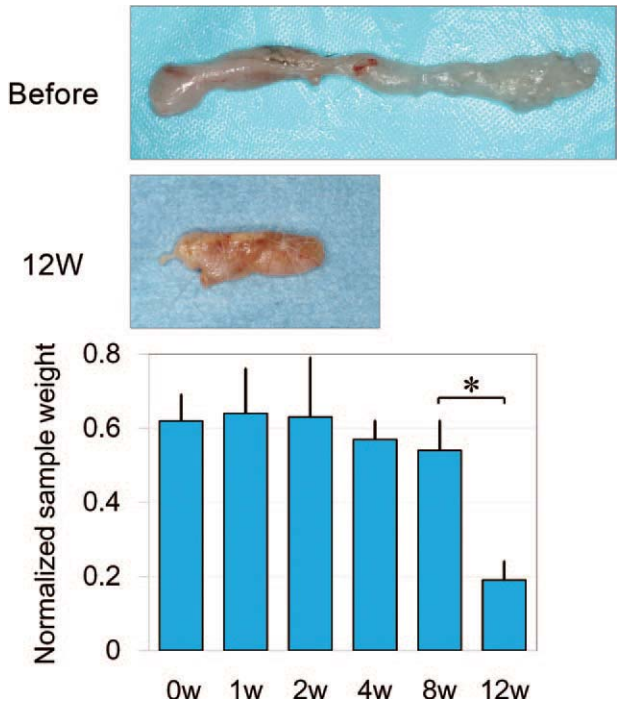

Fig. 1. Grafted fat tissue samples. (*Above*) Macroscopic views of grafted fat samples before and 12 weeks after grafting. (*Below*) Weight of grafted samples. The sample weight was normalized by dividing the sample weight by the body weight. The normalized weight ratio was significantly reduced at 12 weeks, compared with the ratio at baseline. Data are shown as mean ± SEM (*$p < 0.05$).

immunohistology for viable adipocytes in transplanted samples (complete version of Figure 2), ***http://links.lww.com/PRS/A944***. Harvested tissue samples (before and 1, 2, 4, 8, and 12 weeks after grafting) were immunostained for perilipin (cytoplasm of viable adipocytes, green), MAC2 (monocytes/macrophages, red), and Hoechst 33342 (nuclei, blue). Rectangles in the low-magnification images (left column; yellow scale bars = 100 μm) were further magnified in the right column (white scale bars = 30 μm). Demarcation between the surviving and regenerating zone became clear at 1 week (dotted line); dead adipocytes (*) were perilipin-negative and surviving adipocytes were strongly positive for perilipin. Small preadipocytes with multiple intracellular lipid droplets (arrows) appeared around dead adipocytes at 2 to 4 weeks; the dead adipocytes were surrounded by a single layer of macrophages (red). Adipose regeneration was finished by 12 weeks, leaving large lipid drops (#) in the tissue.] The normalized sample weight ratio did not change significantly up to and including 8 weeks, but it exhibited a large decrease between 8 and 12 weeks. The mean normalized weight ratio at 12 weeks (0.19 ± 0.05, $n = 3$) was less than one-third of the ratio at baseline, before grafting (0.62 ± 0.07, $n = 3$).

Dynamic Adipose Tissue Remodeling after Grafting

Viable adipocytes and macrophages were visualized by immunohistochemistry staining for perilipin and MAC2, respectively (Fig. 2) (**See Figure, Supplemental Digital Content 1**, ***http://links.lww.com/PRS/A944***.) At baseline, mature adipocytes (perilipin-positive) with relatively consistent size (70- to 120-μm diameter) and few macrophages ($MAC2^+$) were observed (Fig. 2, *above*). During the first week after fat grafting, many of the adipocytes died, likely because of ischemia as reported previously.[9] At 1 week, demarcation between the surviving superficial area (surviving zone) and the dead deeper area (regenerating or necrotizing zone) was very clear (Fig. 2, *second row*) (**See Figure, Supplemental Digital Content 1**, *second row*, ***http://links.lww.com/PRS/A944***.) because dead adipocytes lost their perilipin stain completely by 1 week. Surviving adipocytes were located superficially below the tissue edge to a depth of 100 to 300 μm.

At 2 and 4 weeks after grafting, new adipocytes, which were strongly positive for perilipin and small (<30 μm), were frequently observed around dead adipocytes in the regenerating zone (Fig. 2, *third row*) (**See Figure, Supplemental Digital Content 1**, *third and fourth rows*, ***http://links.lww.com/PRS/A944***.) These dead adipocytes were surrounded by a single layer of infiltrating macrophages. It was very easy to distinguish dead, shrinking (being absorbed) adipocytes from new, growing adipocytes; the former were perilipin-negative and surrounded by macrophages, whereas the latter were strongly positive for perilipin and frequently contained multiple intracellular lipid droplets.

At 8 weeks after grafting, adipogenesis was finishing and small dead adipocytes were still being absorbed or replaced with fibrotic material. (**See Figure, Supplemental Digital Content 1**, *fifth row*, ***http://links.lww.com/PRS/A944***.) At 12 weeks, adipogenesis was complete, and most of the living adipocytes appeared mature (Fig. 2, *below*) (**See Figure, Supplemental Digital Content 1**, *below*, ***http://links.lww.com/PRS/A944***.) Absorption and fibrous replacement of small dead adipocytes were not yet finished and large lipid drops (accumulated dead adipocytes in the necrotizing zone) remained.

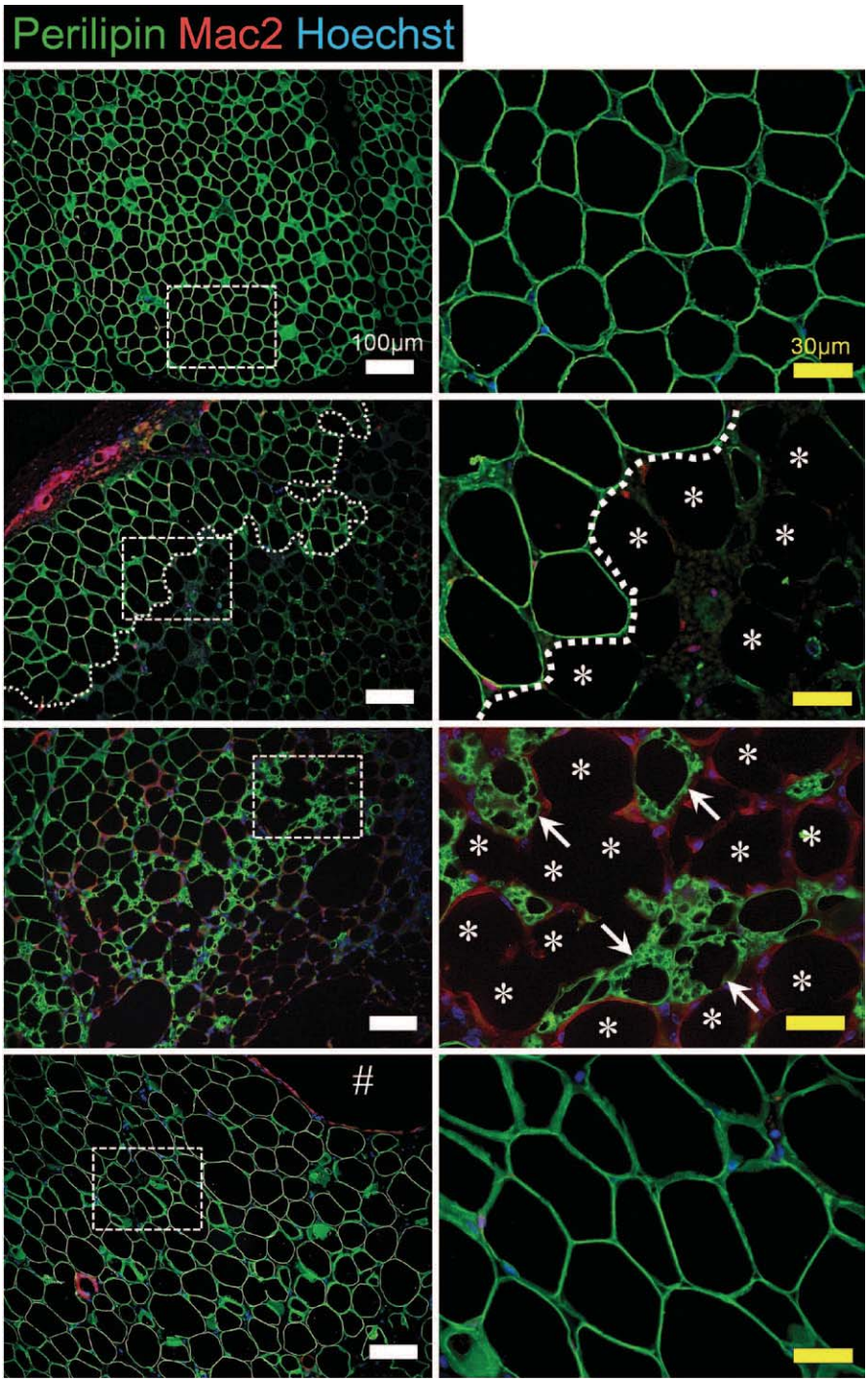

Fig. 2. Immunohistology for viable adipocytes in transplanted samples. Harvested tissue samples obtained before (*above*) and 1 week (*second row*), 4 weeks (*third row*), and 12 weeks (*below*) after grafting were immunostained for perilipin (cytoplasm of viable adipocytes, *green*), MAC2 (monocytes/macrophages, *red*), and Hoechst 33342 (nuclei, *blue*). Rectangles in the low-magnification images (*left column*; *yellow scale bars* = 100 μm) were further magnified in the *right column* (*white scale bars* = 30 μm). Demarcation between the surviving and regenerating zone became clear at 1 week (*dotted line*); dead adipocytes (*) were perilipin-negative and surviving adipocytes were strongly positive for perilipin. Small preadipocytes with multiple intracellular lipid droplets (*arrows*) appeared around dead adipocytes at 4 weeks; the dead adipocytes were surrounded by a single layer of macrophages (*red*). Adipose regeneration was complete at 12 weeks, leaving large lipid drops (#) in the tissue. (See Figure, Supplemental Digital Content 1, for the complete version of this figure, ***http://links.lww.com/PRS/A944***.)

Three Zones in Grafted Tissue: Surviving, Regenerating, and Necrotizing

Three zones were clearly demarcated at 4 weeks: surviving, regenerating, and necrotizing zones (Fig. 3). The most superficial layer (one to several rows of adipocytes) was the surviving zone. The intermediate layer, with a thickness of 600 to 1200 μm, was the regenerating zone, where many new adipocytes were observed adjacent to dead adipocytes. The innermost zone was the necrotizing zone, where new adipocytes were rare and inflammatory cells, oil drops, and fibrous areas were seen (Fig. 3, *above*). Interestingly, although most adipocytes had already died during the first week, the size of the grafted tissue did not change during the first 4 weeks. This indicates that the dead adipocytes generally maintained their size during this time, as the oil drops were slowly absorbed over a period of weeks or months, depending on their size. This seems to be a specific characteristic of mature adipocytes; these cells are extraordinarily large and most of their volume consists of lipid.

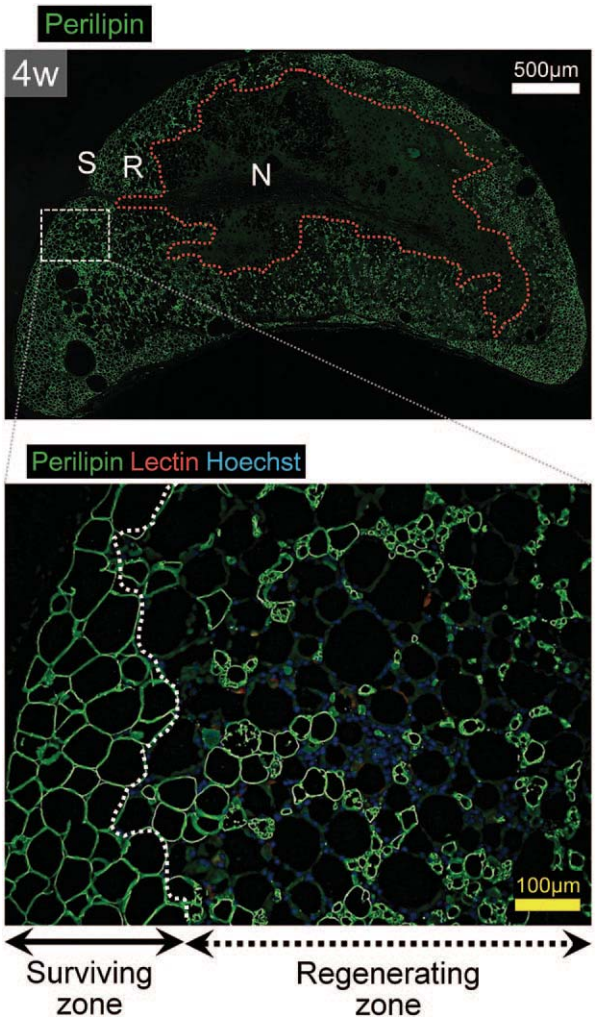

Fig. 3. Three demarcated zones in grafted adipose tissue. Immunohistology of a graft sample at 4 weeks showed demarcated surviving (*S*), regenerating (*R*), and necrotizing (*N*) zones. (*Above*) A low-magnification image of perilipin staining showed the necrotizing zone (*red dotted line*) with few perilipin-positive viable adipocytes (*white scale bar* = 500 μm). (*Below*) A high-magnification image of surviving and regenerating zones (*yellow scale bar* = 100 μm). The surviving zone comprising several layers of perilipin-positive viable adipocytes (*green*) was well demarcated from the regenerating zone (*white dotted line*). Many perilipin-positive small growing adipocytes were seen adjacent to perilipin-negative dark round areas (dead adipocytes not yet absorbed). Vascular endothelial cells and nuclei were stained with lectin (*red*) and Hoechst (*blue*).

Adipogenesis in the Regenerating Zone

The number of new (pre)adipocytes (small adipocytes strongly positive for perilipin), representing ongoing adipogenesis, was counted in immunohistochemical sections (Fig. 4). The number in the regenerating zone increased rapidly after grafting and peaked at 4 weeks. The number of new adipocytes was significantly higher at 1, 2, and 4 weeks than at baseline (0 weeks). Thereafter, the number declined to baseline by 12 weeks, suggesting that adipogenesis for remodeling was complete by 12 weeks.

Cells Surrounding Oil Drops

After adipocyte death during the first week, numerous dead adipocytes (oil droplets with the

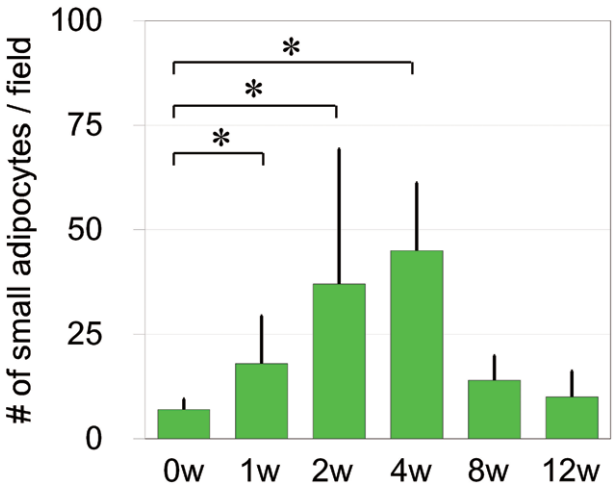

Fig. 4. Sequential changes in number of new adipocytes. Newly born adipocytes (preadipocytes), which are small (<20 μm) and strongly positive for perilipin, were counted. Adipogenesis peaked at 4 weeks and returned to baseline level by 12 weeks (*$p < 0.05$).

size of adipocytes) were seen in the regenerating and necrotizing zones. Every oil drop was surrounded by MAC2$^+$/CD206$^-$ macrophages in the regenerating zone at 2 weeks (Fig. 5, *above*), suggesting that these were inflammatory M1 macrophages scavenging the lipid content. The macrophages formed a single circular layer around each oil drop. By contrast, many macrophages surrounding oil drops in the necrotizing zone were MAC2$^+$/CD206$^+$, suggesting that they were antiinflammatory M2 macrophages. Some of the M2 macrophages were also positive for CD34. Interestingly, the macrophages in the necrotizing zone formed a single circular layer around some oil drops and multiple layers around others.

In the superficial part of the regenerating zone, adipogenesis appeared to be complete at 8 weeks, although some large oil drops remained (Fig. 5, *center*). These oil drops were surrounded by single-layered macrophages. At 12 weeks, adipogenesis appeared to be complete in the border area between the regenerating and necrotizing zone, but oil absorption or replacement with fibrosis was still occurring (Fig. 5, *below*). Oil droplets with the size of adipocytes that were not yet completely absorbed were surrounded by multilayered M2 macrophages (Fig. 5, *below*), whereas some oil droplets were completely absorbed, leaving only the multilayered M2 macrophages (Fig. 5, *below*). These findings likely represent the process of oil drop replacement by fibrosis, mediated by M2 macrophages. These phenomena were not seen in the surviving or superficial regenerating zone but observed only in and around the necrotizing zone. Histopathologic findings shown in Figures 2 through 5 are summarized in Table 1.

Proliferating Cells during the Adipose Remodeling Process

Sequential changes of the number and type of proliferating cells were examined using immunohistochemical sections for Ki67 (Table 2). Although cell proliferation was generally not active until 1 week, numerous proliferative cells were observed in the regenerating and necrotic zones at 2 and 4 weeks. The proliferating cells were predominantly MAC2$^+$ macrophages, and other proliferating cells were CD34$^+$ cells; most of the CD34$^+$ cells were likely adipose stem/progenitor/stromal cells. At 8 weeks, proliferating cells were rare in the regenerating zone, but there were still many proliferating cells in the necrotizing zone, suggesting that remodeling in the regenerating zone was finishing at 8 weeks. Thereafter, the number of proliferating cells in the necrotizing zone decreased over time, but some proliferating cells remained in the necrotizing zone even at 12 weeks, suggesting that dynamic cellular events, such as lipid absorption or fibrosis replacement, were still ongoing.

DISCUSSION

To experimentally simulate human microfat grafting, we selected a mouse model of an autologous fat graft with the inguinal fat pad as donor tissue and the head as the recipient site. The inguinal fat pad is the approximate size of a typical human microfat injection (150 to 200 mg) and it is easy to prepare consistently, although we did not use aspirated fat tissue and it may interfere with the outcomes. Another limitation is that the mouse has little subcutaneous fat tissue and thus the recipient condition is not comparable with that in humans. As the scalp is immobile, it is an ideal location for ensuring postoperative immobilization.

This study reconfirmed the adipocyte replacement theory that we reported previously[9] and presented further details regarding adipocyte replacement with new-generation cells. Demarcation of the surviving zone (100 to 300 μm thick) from the regenerating zone (600 to 1200 μm thick) became clear at 1 week, and new adipocytes (preadipocytes) with intracellular multiple lipid droplets appeared around the dead adipocytes at 1 to 2 weeks, surrounded by a single layer of M1 macrophages (producing a crown-like structure). Adipose stem/progenitor/stromal cells are known to be located perivascularly along the capillaries between adipocytes.[16] We previously showed that adipose stem/progenitor/stromal cells are exceedingly tolerant to ischemia, allowing them to remain alive for up to 3 days under conditions of severe hypoxia.[9] Perivascular adipose stem/progenitor/stromal cells are activated by the death of adjacent adipocytes and give rise to new adipocytes in the regenerating zone if the microenvironment, including the vascularity and oxygen tension, is improved within 3 days after grafting. If capillary growth from surrounding intact tissue does not reach the area and the microenvironment does not improve sufficiently within 3 days, the adipose stem/progenitor/stromal cells will also die, thereby aborting the regenerative process. This area will then become the necrotizing zone.

Interestingly, although most of the adipocytes died after fat grafting, the graft size and weight

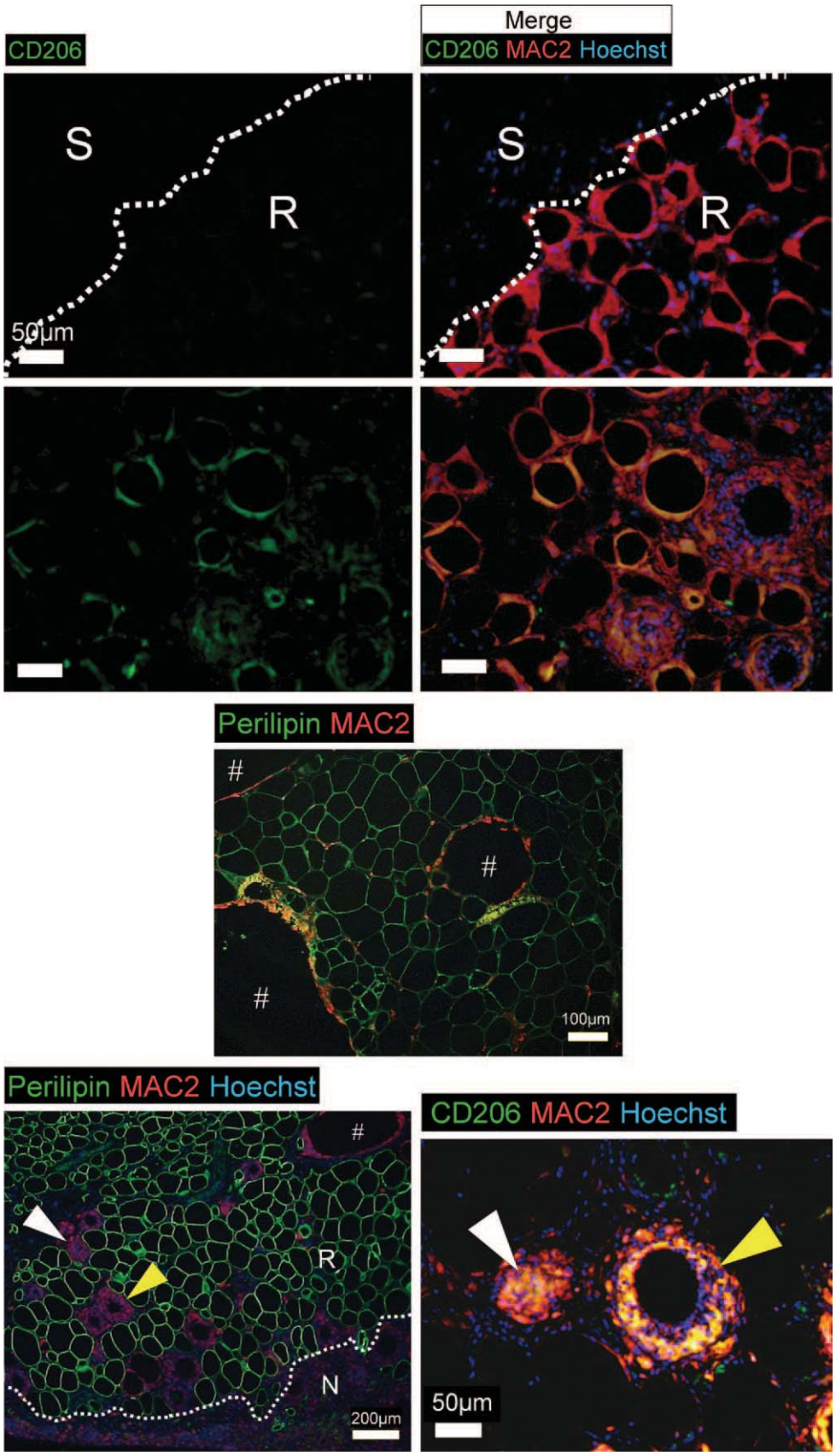

Fig. 5. Histology for macrophages working in adipose remodeling. Macrophages were visualized with immunostaining for MAC2. (*Above*) At 2 weeks, in the regenerating zone (*R*) demarcated

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Table 1. Summary of Histopathologic Findings after Fat Grafting

	General Comments	Surviving Zone	Regenerating Zone	Necrotic Zone
1 wk	Surviving zone is clearly demarcated from other zones where ischemic degeneration is seen. As regeneration is not obvious, regenerating zone is not yet clearly demarcated from necrotizing zone.	Matured adipocytes remain intact (keeping perilipin expression and round shape).	All adipocytes died (lost perilipin expression) and remain as adipocyte-sized oil droplets. Regenerative events are not yet obvious.	All adipocytes died (lost perilipin expression).
2–4 wk	Regeneration is seen and peaked at 4 wk. Scavenging dead adipocytes by infiltrated macrophages progress simultaneously. The border between regenerating zone and necrotizing zone becomes clear.	Same as above.	Numerous growing preadipocytes (small, perilipin-positive, and containing multiple tiny lipid droplets) emerge between crown-like structures (dead adipocytes surrounded by M1 macrophages).	Dead adipocytes and numerous inflammatory cells (lymphocytes and macrophages) are observed, but no regenerative changes such as new preadipocytes are seen. A numerous number of M2 macrophages are seen, as are M1 macrophages. Large oil drops (derived from many dead adipocytes) surrounded by macrophages are seen.
8 wk	Most new adipocytes get matured and the border between surviving zone and regenerating zone become unclear.	Same as above.	Most of the new adipocytes get matured and the number of small adipocytes is small.	No adipogenesis is seen. Many small and large oil drops were seen along with numerous inflammatory cells. Some oil drops are surrounded by multilayered M1 and M2 macrophages, suggesting that fibrogenesis is in progress with scavenging.
12 wk	The total size of the tissue becomes small, probably resulting from accelerated oil absorption. Regeneration appears completed in the regenerating zone, although stabilization of the tissue is not yet completed in the central necrotizing zone.	Same as above.	Tissue is filled with matured adipocytes and appears intact.	The number of small oil drops is reduced, but many large oil drops remain with surrounding inflammatory cells, suggesting that the stabilization process will further need a long time until completed.

did not change significantly until 8 weeks. This observation can be explained by the immunohistologic findings at 2 and 4 weeks. Numerous small oil droplets (adipocyte size; derived from a single dead adipocyte) and large drops (from multiple dead adipocytes) surrounded by macrophages were histologically detected at 1 week and later. However, the oil drops were only slowly absorbed, so they continued to contribute volume and weight to the sample for weeks or even months. Thus, the dead adipocytes functioned as spacers to maintain the grafted tissue volume during the remodeling process; this phenomenon appears to

Fig. 5. (*Continued*) from the surviving zone (*S*), dead adipocytes were surrounded by $MAC2^+CD206^-$ M1 macrophages (*scale bar* = 50 μm). $MAC2^+CD206^+$ M2 macrophages were observed in the necrotizing zone and M1 macrophages. (*Center*) At 8 weeks, the number of perilipin-positive small adipocytes was reduced, suggesting that the regeneration was finishing (*scale bar* = 100 μm). Groups of dead adipocytes formed oil drops (#), which were surrounded by macrophages. (*Below*) At 12 weeks, in border areas between the regenerating (*R*) and necrotizing (*N*) zones, adipogenesis appeared to be complete, but oil absorption and fibrous replacement were still ongoing. In addition to large oil drops (#) surrounded by macrophages, adipocyte-sized macrophage clusters were observed with (*yellow arrowheads*) or without (*white arrowheads*) lipid droplets inside (*left*; *scale bar* = 200 μm). The lipid droplet–containing macrophage cluster was composed of an innermost single layer of M1 macrophages ($MAC2^+CD206^-$) and outer multilayered M2 macrophages ($MAC2^+CD206^-$) (*right*; *scale bar* = 50 μm). It is suspected that M2 macrophages appeared in unfavorable conditions where adipocyte regeneration failed and fibrous replacement of the space was needed.

Table 2. Type and Localization of Proliferating Cells

	Surviving Zone	Regenerating Zone	Necrotizing Zone
Before	–	–	–
1 wk	–	+ ($MAC2^+ > CD34^+$)	–
2 wk	–	+++ ($MAC2^+ > CD34^+$)	+++ ($MAC2^+ > CD34^+$)
4 wk	–	+++ ($MAC2^+ > CD34^+$)	+++ ($MAC2^+ > CD34^+$)
8 wk	–	–	++ ($MAC2^+ > CD34^+$)
12 wk	–	–	+ ($MAC2^+ > CD34^+$)

facilitate the dynamic adipocyte replacement by activated adipose stem/progenitor/stromal cells.

Our results suggest that the first 3 months after transplantation is a period of tissue repair and that adipogenesis will not occur after this period. After the initial ischemic damage to the tissue, inflammatory cells infiltrated the grafted tissue, initially entering the regenerating zone and then the necrotizing zone. In the regenerating zone, adipogenesis and angiogenesis progressed and many of the dead adipocytes were replaced with next-generation adipocytes, which probably originated from tissue-resident adipose stem/progenitor/stromal cells. In parallel with the regenerating events, stabilizing events, such as lipid absorption (phagocytosis) and lipid replacement with scar tissue (fibrosis), occurred. Both the regenerating and stabilizing processes progressed from the superficial layers of the regenerating zone to the deeper layers over the first 3 months. Although the regeneration process peaked at 4 weeks and was complete by 3 months, the stabilizing process was not finished at 3 months. The stabilizing process may persist for at least several more months, as suggested by clinical observations that volume reduction after fat grafting continues until the end of the first year. Our findings also showed that adipocyte-sized oil droplets were absorbed or temporarily filled with multilayered M2 macrophages, producing fibrosis, but substantially larger oil drops may form oil cysts in several months and remain permanently.

Immunohistologic assessment for Ki67 demonstrated the presence of proliferative cells during the remodeling process. $Ki67^+/CD34^+$ cells (proliferating more) appeared at 1 week, increased in number at 2 to 4 weeks in the regenerating zone, and thereafter decreased gradually, suggesting that these cells are associated with adipogenesis/angiogenesis. However, a majority of the proliferating cells in the repair period were not adipose stem/progenitor/stromal cells, but were $MAC2^+$ monocytes/macrophages, which were seen in both the regenerating and necrotic zones. $Ki67^+/MAC2^+$ cells appeared as single or multiple layers of cells surrounding oil droplets, suggesting that M1 and M2 macrophages continued to proliferate during the stabilizing process. Proliferating anti-inflammatory M2 macrophages originating locally have been reported in various inflammatory conditions.[17–20] The number of $Ki67^+/MAC2^+$ cells decreased gradually after 4 weeks, reflecting the changing dynamics of the remodeling process.

Our results suggested that two different types of macrophages, M1 and M2 macrophages, may have distinct roles: phagocytosis and fibrosis (or managing the dead space), respectively. M2 macrophages appeared at later stages than M1 macrophages, and they were frequently observed in deeper zones, suggesting that M2 macrophages have a biological role in working under unfavorable microenvironments, such as severe ischemia. Two types of small oil droplets were observed: adipocyte-sized oil droplets surrounded by a single layer of M1 macrophages and smaller oil droplets surrounded by multiple, stratified macrophages (an inner single layer of M1 macrophages and outer multiple layers of M2 macrophages). These findings suggest that M2 macrophages contribute to filling the dead space with fibrous tissue in parallel with lipid absorption in the deeper regenerating and necrotic zones.

Based on the results of the present study, we have summarized the fate of adipocytes in grafted adipose tissue in Figure 6. The fate of these cells depends on the microenvironment (such as vascularity and oxygenation) in which each adipocyte is placed. Adipocytes remain alive in the surviving zone, whereas they die shortly after grafting in the regenerating and necrotizing zones. On adipocyte death, adjacent adipose stem/progenitor/stromal cells are activated and begin to differentiate into adipogenic lineage cells in the regenerating zone, whereas adipose stem/progenitor/stromal cells also die in the necrotizing zone. Dead adipocytes under better conditions in the regenerating zone are phagocytized by M1 macrophages and are successfully replaced by new adipocytes without residual fibrosis. By contrast, dead adipocytes under worse conditions in the regenerating or necrotizing zones are surrounded by M1 and M2 macrophages; oil absorption by M1 macrophages occurs along with fibrous replacement of the space (fibrogenesis) by M2 macrophages. In the necrotizing zone, many large oil drops, derived from a group of dead adipocytes, are formed, which are also surrounded by M1 and M2 macrophages. The time required for oil absorption is generally proportional to the oil drop diameter, and oil absorption and fibrous replacement are not complete within 3 months for large oil drops. For these drops, complete absorption of the oil content may occur for many more months or a cystic wall may form that prohibits total absorption.

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CONCLUSIONS

This study revealed the underlying mechanisms of successful (regeneration) and unsuccessful (cicatrization) tissue remodeling, which

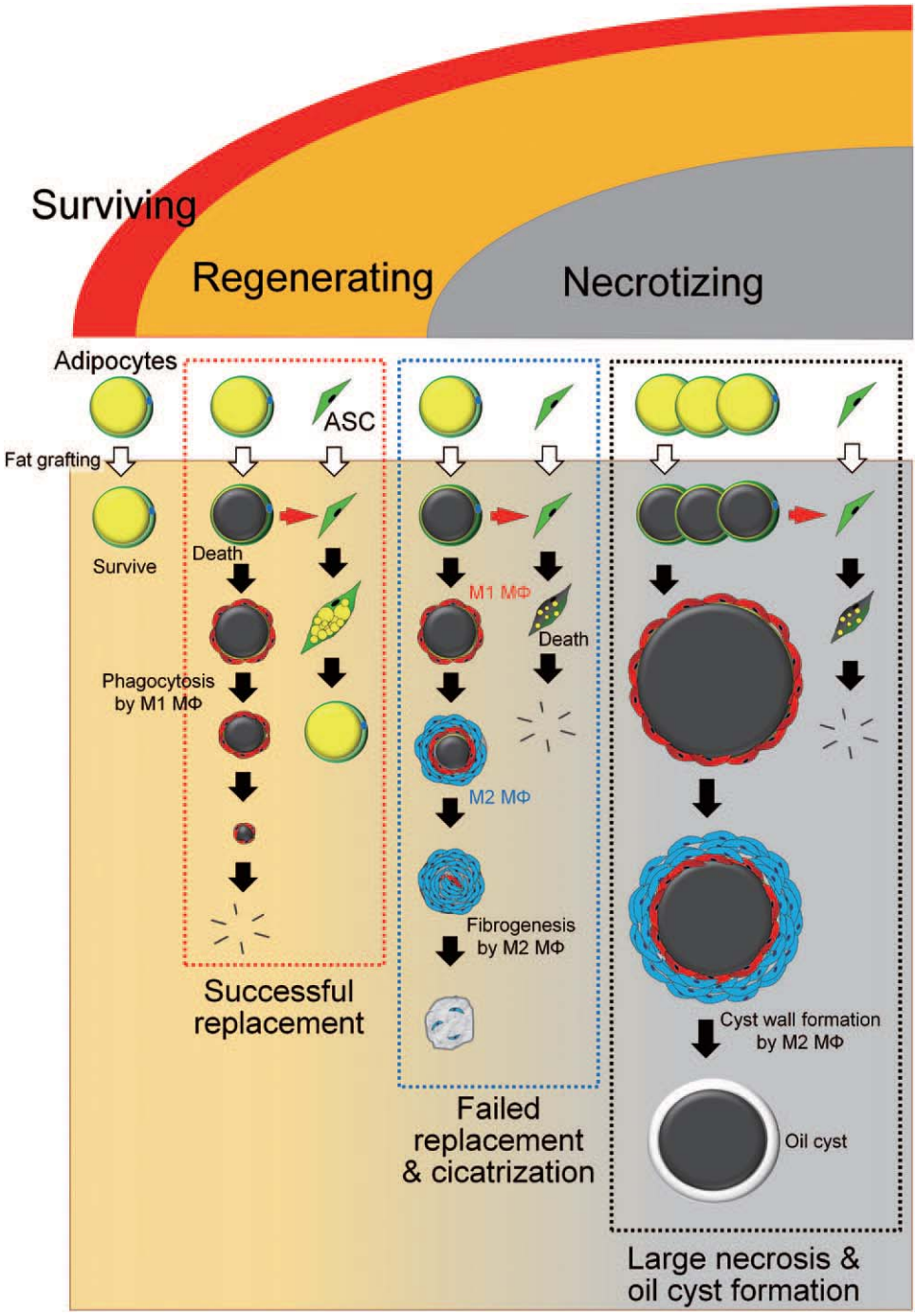

Fig. 6. Conclusive schema for the fate of adipocytes in grafted fat. During the first 3 months of adipose tissue remodeling, transplanted adipocytes have differential fates depending on their microenvironments. In this schema, complex cellular events are simplified and the adipocyte fate is categorized into four patterns: survival, successful regeneration, failed regeneration (cicatrization), and oil cyst formation. Cicatrization and oil cyst formation are often not complete at 3 months. *ASC*, adipose stem/progenitor/stromal cells.

should facilitate the future development of strategies to improve the clinical outcome of fat grafting. Grafted fat tissue undergoes degeneration during the first week, and regeneration peaked at 4 weeks. Adipose tissue-resident progenitor cells contribute to the regeneration, and M1 and M2 macrophages play pivotal roles in phagocytosis and cicatrization, respectively, in the regenerating

and necrotizing zones. The stabilization process after failed regeneration appears to persist for a long time. The size of the necrotizing zone depends predominantly on the size of the grafted tissue and the microenvironment into which it is placed. Necrotic zones will eventually be absorbed, filled with fibrous tissue, or become a problematic cyst. To minimize the size of the necrotic zone, liposuction and reinjection procedures could be improved by preparing grafts with better viability and an appropriate size, maximizing the contact surface of the grafts by ideal distribution, and placing the grafts in areas with high vascularity. Stabilization of the grafted fat may not occur until many months after complete regeneration at 3 months, thereby emphasizing the importance of long-term follow-up to thoroughly evaluate the clinical results of micro–fat-grafting procedures.

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