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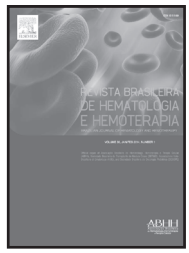

Review article

Obesity and inflammation and the effect on the hematopoietic system

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ABSTRACT

Bone marrow is organized in specialized microenvironments known as 'marrow niches'. These are important for the maintenance of stem cells and their hematopoietic progenitors whose homeostasis also depends on other cell types present in the tissue. Extrinsic factors, such as infection and inflammatory states, may affect this system by causing cytokine dysregulation (imbalance in cytokine production) and changes in cell proliferation and self-renewal rates, and may also induce changes in the metabolism and cell cycle. Known to relate to chronic inflammation, obesity is responsible for systemic changes that are best studied in the cardiovascular system. Little is known regarding the changes in the hematopoietic system induced by the inflammatory state carried by obesity or the cell and molecular mechanisms involved. The understanding of the biological behavior of hematopoietic stem cells under obesity-induced chronic inflammation could help elucidate the pathophysiological mechanisms involved in other inflammatory processes, such as neoplastic diseases and bone marrow failure syndromes.

Introduction

Bone marrow is an animal tissue with one of the highest cell proliferation rates. It gives rise to components of all hematopoietic and immune system lineages. In humans, approximately 1×10^{11} to 1×10^{12} mature blood cells are produced daily, due to the division and proliferation of a population of hematopoietic stem cells (HSCs), with a unique capacity for self-renewal and multilineage differentiation.[1]

The organization of bone marrow in specialized microenvironments, the 'marrow niches,' is important for the maintenance of hematopoietic stem and progenitor cells, as

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well as their intramedullary localization and cell cycle phase.[2] Although the majority of HSCs were originally believed to be quiescent, many studies have demonstrated that these cells are actually cycling, although very slowly, suggesting a state of dormancy.[3] They are activated for more intense proliferation and differentiation under stress conditions, when demands are higher (i.e. during infection) or for replacement of cells eliminated by cell death.[2] In fact, many progenitors already committed to specific lineages appear to cycle actively. This condition strengthens the idea that the proliferation of HSCs and their progenitors is regulated by factors external to the cell itself, which must involve the action of different niches.[4-6] Osteoblasts, endothelial cells, macrophages and other more primitive mesenchymal cells exert, by mechanisms not yet fully elucidated, a direct effect on the control of hematopoiesis.[7]

The identification and distribution of bone marrow niches has been the subject of intense scientific debate. For example, HSCs have been shown to be in direct contact with a population of osteoblasts, which delimit the bone marrow surface. Osteoblasts are characterized by their fusiform shape and high expression of N-cadherin, called SNO cells (spindle-shaped N-cadherin$^+$ CD45$^-$ osteoplastic cells), which form the so-called 'endosteal niche'.[8] Many HSCs are also close to the sinusoidal endothelium, suggesting that endothelial cells could also create clusters for HSCs (the vascular niche).[9] Another recently discovered cell type that seems to play a key role in the maintenance of HSCs is the 'CAR cell' (CXCL12-abundant reticular cell), a small population of reticular cells expressing high amounts of CXCL12.[10] CXCR4, the CXCL12 receptor, has been shown to be critical to maintain the HSCs pool and progenitor B cells in the bone marrow in direct contact with CAR cells, suggesting an important role of these cells in hematopoietic regulation .[11]

Knowledge of the different rates of stem cell proliferation and their regulation by other cell types in homeostasis has raised questions regarding possible changes in these mechanisms and the relationship between infection and the hematopoietic niche along with HSC modulation. Factors such as the association between HSC exposure to toll-like receptor (TLR) ligands and osteoclasts maturation,[12] in addition to the increase in granulocyte-colony stimulating factor (G-CSF) expression and the increase in the peripheral mobilization of HSCs,[13] reinforce the association between infection and modulation of HSC biology.

In addition to the direct effects caused by the pathogens or pathogenic particles, changes in the clusters of HSCs and their biological activity in response to infection may also indirectly be mediated by pro-inflammatory cytokines. In a recent study, Chen et al. demonstrated that HSCs exposed to a combination of lipopolysaccharide-induced proinflammatory cytokines, Interleukin (IL)-6, tumor necrosis factor (TNF) and chemokine ligand 2 (CCL2), showed a decrease in the potential of marrow repopulation and long-term engraftment, while maintaining the proliferation potential.[14] In a *Mycobacterium avium* infection model in mice, activation of HSCs was initiated by interferon-gamma (INF-g) signaling.[15] However, high levels of INF-g are known to be capable of inducing apoptosis in hematopoietic cells, leading to bone marrow hypocellularity. In fact, exposure of human CD34$^+$ cells to INF-g leads to the expression of pro-apoptotic genes in vitro[16] and continuous exposure to INF-g has also been related to a reduction in colony formation of human bone marrow cells in cultures.[17]

The duration and conditions of exposure to interferon and other inflammatory cytokines could be crucial factors regulating the biological activity of HSCs. Different responses to inflammatory cytokines may explain, for example, the mechanisms that lead to some bone marrow failure syndromes. It is because of this that these factors represent important areas for future scientific research.

Obesity and chronic inflammation and the hematopoietic system

The association between obesity and low-grade chronic inflammation has been demonstrated in numerous studies.[18-20] Inflammation has been implicated in the pathophysiology of many morbid complications observed in most obese individuals, through mechanisms that go beyond a positive caloric balance, such as the release of adipokines and interleukins.[21] Originally considered a mechanism of energy reservoir, adipose tissue is now recognized as one of the body's largest endocrine organs, secreting a variety of substances that exert multiple regulatory activities involving glucose homeostasis, immune function and metabolism.[19] Given the systemic nature of this process, it is plausible that changes in the hematopoietic and immune systems may occur due to obesity.

Experiments involving animal models have demonstrated that high-fat diet (HFD)-induced obesity is associated with high levels of acute-phase reactants and leukocytosis, in addition to higher bone marrow cellularity, mainly due to polymorphonuclear expansion.[22] One possible mechanism postulated to explain the augment in granulopoiesis is an increased production of G-CSF by bone marrow cells in the obese group compared to controls.[23] Moreover, mesenchymal stem cells (MSC) of HFD rats express considerably higher amounts of nuclear Factor kappa β (NF-kβ) as well as tumor necrosis factor alpha (TNFα), IL-1 and IL-6, which can inhibit adipocyte differentiation of MSC thus shifting bone marrow differentiation towards osteoblasts. This mechanism could be responsible for niche alterations affecting marrow microenvironments and consequently destabilizing hematopoietic cell numbers and peripheral mobilization in the inflammatory state.[22]

In humans, obesity is associated with a peripheral blood increase of white blood cell counts, correlating with increased levels of C-reactive protein and decreased IL-10.[24,25] Disturbances in erythropoiesis have also been described, including anemia and alterations in iron homeostasis.[26] Interestingly, increased levels of IL-6 and leptin induced by inflammation result in the release of hepcidin from the liver and adipose tissue.[27,28]

Hepcidin is an important regulator of iron homeostasis, inhibiting iron absorption by enterocytes and the sequestration of iron by macrophages that result in restricted erythropoiesis leading to mild/moderate anemia.[29] Obesity is associated with high levels of hepcidin, independently of the presence

of liver alterations,[27] suggesting that the anemia experienced by obese individuals may be secondary to the inflammatory status (anemia of chronic disease), in addition to the direct effects of cytokines on the proliferation and differentiation of erythroid progenitors.

In fact, studies involving patients undergoing bariatric surgery as treatment of obesity have clarified the fact that anemia in this population cannot be explained solely on the basis of iron availability and nutritional status.[30,31] Drygalski et al. assessed 1125 obese patients before and after bariatric surgery for the prevalence of anemia and the depletion of body iron stores. The baseline incidence of anemia was higher than expected and increased significantly after surgery as the overall iron bioavailability improved significantly with pronounced weight loss, possibly following the reduction in inflammation.[31] Gastric bypass surgery was also associated with a generalized decrease in the white blood cell and platelet counts, although not clinically important.[32] These findings suggest that generalized suppression of hematopoiesis might occur after surgery, revealing a possible hyperproliferative state triggered by inflammation in obese patients.

Bioenergetic organization of stem cells in obesity

One of the striking features of the HSC niche is its low oxygen tension, yielding the term 'hypoxic niche.' This microenvironment of low O_2 concentrations appears not only to be well tolerated by HSCs but also essential for keeping their self-renewal and differentiating properties.[33-36]

Through mitochondrial metabolism, O_2 generates reactive oxygen species (ROS) that, at increased levels, lead to cell dysfunction and aging, disrupting tissue homeostasis. The aberrant production of large quantities of ROS in mitochondria has been implicated in the pathophysiology of several chronic degenerative processes, such as Parkinson and Alzheimer's diseases,[37] and this seems to act in deleterious ways also in obesity, diabetes and metabolic syndrome.[38] Thus, the distribution of stem cells in hypoxic niches with reduced ROS production seems clearly advantageous.[39] Maintaining viability in a hypoxic environment, however, could require HSCs to have great metabolic adaptions; these mechanisms however are not yet fully known.

Cellular bioenergetic homeostasis is determined by the fraction of cellular adenosine triphosphate (ATP) produced by glycolysis or mitochondrial oxidative phosphorylation (OXPHOS). In some situations, as previously described in tumors, bioenergetic organization is different from normal cells', wherein the method of ATP production switches progressively from oxidative phosphorylation to glycolysis, which is called the 'Warburg effect'.[40] This distinct metabolism results from the dysregulation of multiple oncogenes and tumor suppressor genes, whose final target is the glycolytic pathway,[41] in addition to defects in the mitochondria itself. This mechanism may be responsible for better adaptation of tumor cells to microenvironments with chronic or intermittent hypoxia, in addition to reducing mitochondria-dependent cell death, facilitating invasion and metastasis.[42]

Suppression of oxidative phosphorylation generates signals to adenosine monophosphate-activated protein kinases (AMPK), which reprogram cellular metabolism, stimulating glycolysis through increased cellular glucose uptake and activating 6-fosfofruto-2-kinase. Meanwhile, activated AMPK also inactivates enzymes responsible for ATP consumption including, for example, those involved in fatty acid and cholesterol synthesis.[43] In addition to these effects, activation of AMPK also suppresses cell proliferation in normal and neoplastic tissues.[44]

Increased AMPK after oxidative phosphorylation suppression is known to be transient. However, whether the maintenance of anaerobic conditions after normalization of AMPK could lead to the death of these cells, or whether any such mechanism would be only the initial part of an adaptive process by giving more advantage to these tissues, is not clear yet .[45]

An important mechanism of adaptation to hypoxia involves hypoxia-inducible factor 1 (HIF-1), a heterodimeric transcription factor composed of an O_2-regulated subunit (HIF-1α) and a constitutional subunit (HIF-1β).[46] The two subunits are present in all human and murine tissues and are activated by O_2-dependent hydroxylases. The final action occurs primarily through modulation of transcription of other genes involved in the cell metabolism.[47]

Another event that appears to be important for adaptation to hypoxia is the exchange of the regulatory subunit of the cytochrome c oxidase from cyclooxygenase COX4-1 to COX4-2; the latter being activated by HIF-1. Other mitochondrial proteases are also activated by HIF-1, leading to enhanced degradation of COX4-1.[48] This mechanism appears to be essential for the optimal function of cytochrome c oxidase in situations of hypoxia and to reduce ROS production.

Recently, a mechanism to minimize cell damage caused by excess ROS production, dependent on the action of uncoupling proteins (UCP) has been elucidated. Part of the proton gradient used to drive the synthesis of ATP is deflected from the membrane back into the mitochondrial matrix, thereby reducing the emission of ROS, this transport is carried out by UCP 'uncoupling' the oxidative phosphorylation process.[49] Three isoforms of UCP (UCP-1, -2 and -3) have been described and all appear to be activated by ROS molecules themselves, setting up a negative feedback loop.

Thus, we can speculate that obesity and its related deregulations in metabolism and inflammation may alter bone marrow niches and the energetic organization of marrow cells through pathways that have not been fully investigated until now.

Conclusion

Biologically, obesity is characterized by a state of chronic inflammation and its effects on the hematopoietic system, in particular on the stem cell compartment, are poorly understood. Therefore, further studies are needed to clarify the specific impact of this state at molecular and cellular levels, as well as the mechanisms involved. Long-term activation of hematopoietic stem cells during chronic inflammation may lead to the depletion of these cells or development of

functional defects, such as those seen in aplastic anemia. Therefore, this area of research may also provide new evidence to understand other situations involving chronic inflammation, such as normal aging, neoplastic diseases and bone marrow failure syndromes.

The evaluation of the proliferative and self-renewal potential of hematopoietic cells, the cytokine and hematopoietic growth factor profiles of obese individuals and the bioenergetic organization of stem cells in obesity are some key points for future investigation.

Conflicts of interest

The authors declare no conflicts of interest.

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