Quantitative Analysis of Cobblestone Area-Forming Cells in Bone Marrow of Patients With Aplastic Anemia by Limiting Dilution Assay

By Hubert Schrezenmeier, Marianne Jenal, Friedhelm Herrmann, Hermann Heimpel, and Aruna Raghavachar

In the past, the analysis of primitive human hematopoietic progenitor cells with repopulating activity was limited by lack of appropriate in vitro assay systems. It was recently shown that cobblestone area-forming cells (CAFC) giving rise to cobblestone areas after 5 weeks in long-term marrow cultures (LTMC) represent a population of pluripotent progenitor cells with long-term marrow-repopulating activity. We have used a microtiter limiting-dilution-type human LTMC system to quantitate the frequency of CAFC (week 5) in aplastic anemia (AA). In bone marrow mononuclear cells (BM-MNC) of healthy donors (n = 36) we observed a mean frequency of 84.4 CAFC per \(10^6\) BM-MNC (95% confidence interval limits, 66.4 to 102.4). The mean frequency of CAFC in BM of 31 AA patients was 6.6 per \(10^6\) BM-MNC (95% confidence interval limits, 5.3 to 7.9; n = 47). This frequency is significantly lower as compared with controls (P < .0001).

Several pathogenetic mechanisms have been proposed to account for the bone marrow (BM) failure in aplastic anemia (AA). These include an intrinsic defect of hematopoietic stem cells, lymphocyte-mediated suppression of hematopoiesis, dysfunctions of the BM microenvironment, and abnormalities in regulation of hematopoiesis by humoral factors.\(^4\)\(^5\) Several studies have shown that AA patients who responded to immunosuppressive treatment are at high risk for relapse of aplasia\(^4\) or for the evolution to clonal disorders of hematopoiesis.\(^5\)\(^9\) These clinical observations suggest that patients in remission are not cured of their disease but that some pathophysiologic conditions might have persisted in responders after immunosuppressive treatment.

Short-term cultures have shown a significant reduction in all types of committed hematopoietic progenitor cells.\(^10\)\(^14\) This defect does not normalize after response to immunosuppressive treatment.\(^10\)\(^14\) A hematopoietic defect is also demonstrable in long-term marrow cultures (LTMC) of AA marrow. Compared with controls, the number of colony-forming units–granulocyte-macrophage (CFU-GM) produced in LTMC of AA marrow is significantly lower and CFU-GM are detected in LTMC for a shorter period of time.\(^15\)\(^18\) However, neither the measurement of committed progenitors\(^10\) nor the analysis of growth in standard-type LTMC\(^15\)\(^18\) allows the enumeration of very primitive hematopoietic cells. Combination of LTMC with limiting dilution method makes a quantitative assessment of primitive cells feasible.

The frequency of CAFC was reduced not only in pancytopenic AA patients (6.2 per \(10^6\) BM-MNC; P < .0001 v control), but also in patients in remission after immunosuppression (7.6; P < .0001 v control; P = .1 v pancytopenic AA patients). The CAFC frequency did not correlate with the severity or duration of the disease and did not predict response to immunosuppressive treatment. In summary, the frequency of primitive hematopoietic progenitor cells, as measured by the CAFC assay, is significantly reduced in AA. CAFC remain severely reduced even after hematologic recovery after immunosuppressive treatment. The low frequency of CAFC in remission patients is in keeping with other data pointing to a persisting defect of hematopoiesis in patients in remission after immunosuppressive treatment.

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apy as outlined in Table 1: antilymphocyte globulin (ALG; Lymphoglobulin Merieux; Institut Merieux, Leimen, Germany) at 0.75 mL/kg intravenously (IV) for 8 days, methylprednisolone (MP) at 5 mg/kg for days 1 through 8 and tapering until day 29, cyclosporin A (CyA; Sandimmun; Sandoz, Nürnberg, Germany) at 5 to 12 mg/kg orally initially, with dose adjustment according to blood trough levels for 3 months.26-28 Granulocyte colony-stimulating factor (G-CSF; Neupogen; Amgen, Thousand Oaks, CA) was administered at 5 μg/kg subcutaneously daily until day 112. Monoclonal antibody directed against the interleukin-2 receptor (IL-2R MoAb; BMS-3;...
After 14 days, nonadherent cells were removed by washing. The medium succinate (Sigma, Munich, Germany) in 6-well tissue culture plates (Nunc). BM cells from all donors formed a confluent stroma. BM-MNC were set up in triplicate in 96-well flat-bottomed plates (Nunc, Nürtingen, Germany) and were incubated at 33°C in a humidified atmosphere. The agar layers were then dried onto glass slides, stained, and counted by light microscopy (colonies >40 cells). For analysis of colony-forming units-erythroid (CFU-E) and burst-forming units-erythroid (BFU-E), cells were plated in 0.9% (vol/vol) methylcellulose in IMDM with 20% (vol/vol) preselected FCS, and 5% (vol/vol) human placenta-derived water. The agar layers were then dried onto glass slides, stained, and counted by light microscopy (colonies >40 cells). For analysis of colony-forming units-erythroid (CFU-E) and burst-forming units-erythroid (BFU-E), cells were plated in 0.9% (vol/vol) methylcellulose in IMDM with 20% (vol/vol) FCS, and 5% (vol/vol) human placenta-derived water. The agar layers were then dried onto glass slides, stained, and counted by light microscopy (colonies >40 cells). For analysis of colony-forming units-erythroid (BFU-E), cells were plated in 0.9% (vol/vol) methylcellulose in IMDM with 20% (vol/vol) FCS, and 5% (vol/vol) human placenta-derived water. The agar layers were then dried onto glass slides, stained, and counted by light microscopy (colonies >40 cells).

Preparation of Cells
After informed consent was obtained, BM from patients with AA and healthy controls was collected by aspiration from the posterior iliac crest. BM mononuclear cells (BM-MNC) were separated on Lymphoprep (1.077 g/mL; Nycomed, Oslo, Norway). BM-MNC were washed and resuspended in Iscove's modified Dulbecco's medium (IMDM; Gibco, Eggenstein, Germany) with 20% (vol/vol) preselected fetal calf serum (FCS; Gibco). Colony Assays
For analysis of CFU-GM, the BM-MNC (equivalent to 2 × 10^6 cells/culture well) were plated into a layer composed of 0.3% agar, 20% (vol/vol) preselected FCS, and 5% (vol/vol) human placenta-derived water. The agar layers were then dried onto glass slides, stained, and counted by light microscopy (colonies >40 cells). For analysis of colony-forming units-erythroid (CFU-E) and burst-forming units-erythroid (BFU-E), cells were plated in 0.9% (vol/vol) methylcellulose in IMDM with 20% (vol/vol) FCS, and 5% (vol/vol) human placenta-derived water. The agar layers were then dried onto glass slides, stained, and counted by light microscopy (colonies >40 cells). For analysis of colony-forming units-erythroid (BFU-E), cells were plated in 0.9% (vol/vol) methylcellulose in IMDM with 20% (vol/vol) FCS, and 5% (vol/vol) human placenta-derived water. The agar layers were then dried onto glass slides, stained, and counted by light microscopy (colonies >40 cells). For analysis of colony-forming units-erythroid (BFU-E), cells were plated in 0.9% (vol/vol) methylcellulose in IMDM with 20% (vol/vol) FCS, and 5% (vol/vol) human placenta-derived water. The agar layers were then dried onto glass slides, stained, and counted by light microscopy (colonies >40 cells).

Limiting Dilution-Type Micro-LTMC
Preparation of stroma layers. BM cells from healthy donors were incubated at a concentration of 1 × 10^6 cells/mL in myeloid LTMC-medium (Stem Cell Technologies, Vancouver, British Columbia, Canada) supplemented with 10^-6 mol/L hydrocortisone sodium succinate (Sigma, Munich, Germany) in 6-well tissue culture plates (Nunc). BM cells from all donors formed a confluent stroma (ie, >75% of culture plate covered by stromal cells) within 14 days. After 14 days, nonadherent cells were removed by washing. The adherent cells were suspended by treatment with trypsin and were incubated in 0.1 mL LTMC medium per well in 96-well flat-bottomed microwells (Nunc) at 35°C. After 2 to 4 days, a confluent adherent layer of cells had been established in the microwells. The layers were then irradiated with 15 Gy. This radiation dose proved to be sufficient to eliminate hematopoietic activity (data not shown). In BM of 36 healthy controls, the mean absolute number of CFU-E was 84.4 per 10^6 BM-MNC (95% confidence interval [CI] limit, 66.4 to 102.4). In 47 CAFC assays performed

RESULTS
BM-MNC of controls and AA patients were overlaid on preformed irradiated allogeneic stroma layers. The allogeneic stroma layers were capable of supporting the formation of cobblestone areas. First, the relationship between the number of BM-MNC that were initially overlaid on the stroma layer and the number of cobblestone areas present after 35 days of culture was investigated. Figure 1 shows a representative experiment with BM-MNC from a control and a patient with AA (m). The slope of the linear regression of the logarithm of the values is 1.42 (healthy donor) and 1.23 (AA). The probability that the slope is significantly different than 0 is P = .0001 (control) and P = .0008 (AA).

Fig 1. The number of cobblestone areas per culture (day 35) are plotted against the number of input cells seeded on the stromal cell layer for a representative experiment with BM-MNC of a healthy donor (●) and a patient with AA (●). The slope of the linear regression of the logarithm of the values is 1.42 (healthy donor) and 1.23 (AA). The probability that the slope is significantly different than 0 is P = .0001 (control) and P = .0008 (AA).

The frequency of progenitors giving rise to a cobblestone area after 35 days of culture was determined in limiting dilution experiments. Examples of limiting dilution experiments comparing the frequency of CAFC in AA and control BM-MNC are shown in Fig 2. Assuming a single-hit model, the frequency of CAFC was calculated using the maximum likelihood method with iterative approximations as described by Taswell. The frequency of progenitors giving rise to a cobblestone area after 35 days of culture was determined in limiting dilution experiments. Examples of limiting dilution experiments comparing the frequency of CAFC in AA and control BM-MNC are shown in Fig 2. Assuming a single-hit model, the frequency of CAFC was calculated using the maximum likelihood method with iterative approximations as described by Taswell.

In BM of 36 healthy controls, the mean absolute number of CAFC was 84.4 per 10^6 BM-MNC (95% confidence interval [CI] limit, 66.4 to 102.4). In 47 CAFC assays performed...
with BM-MNC of 31 AA patients, the mean frequency of CAFC was significantly reduced to 6.6 CAFC per $10^5$ BM-MNC (95% CI limit, 5.3 to 7.9; $P < .0001$ compared with healthy controls). CAFC were significantly reduced compared with controls both in BM of cytopenic AA patients and AA patients in remission after treatment. The absolute number of CAFC per $10^5$ BM-MNC of controls and AA patients is depicted in Fig 3. In pancytopenic AA patients, the mean frequency of CAFC was 6.2 per $10^5$ BM-MNC (95% CI limit, 4.6 to 7.8; $P < .0001$, compared with healthy controls). In 13 patients who were analyzed after they had achieved at least a partial response to immunosuppressive treatment, the mean frequency of CAFC was still significantly lower than in controls (7.6 per $10^5$ BM-MNC; 95% CI limit, 4.9 to 10.4; $P < .0001$ compared with controls).

The difference in CAFC numbers between aplastic AA patients and AA patients in remission after treatment is not statistically significant ($P = .1$). The absolute CAFC numbers of 13 patients who were analyzed at several occasions during the course of the disease are shown in Fig 4. It is shown that patients with low CAFC numbers at diagnosis continue to have low CAFC after immunosuppression even if they had entered remission.

The number of CAFC in BM did not reflect the severity of the aplasia. There was no correlation of CAFC number and severity of the disease or the remission status at time of CAFC analysis (Table 2). Furthermore, there was no correlation between the number of CAFC and the response to immunosuppressive treatment ($P = .58$; data not shown). The reduction in the frequency of CAFC did not correlate with the duration of aplasia (coefficient of correlation, .12; $P = .42$).

The mean frequencies of BM CFU-GM, BFU-E, and CFU-E in controls and patients with AA are listed in Table 3. The number of committed progenitor cells was significantly reduced both in aplastic AA patients and in patients after response to treatment as compared with controls. In contrast to CAFC, committed progenitor cells were higher in AA patients in remission compared with patients in aplasia.

### Table 2. CAFC Frequency in BM-MNC of Patients With Aplastic Anemia Stratified for Severity of Disease and Response to Immunosuppressive Treatment

<table>
<thead>
<tr>
<th>Status at CAFC assay</th>
<th>n</th>
<th>Mean</th>
<th>95% CI Limits</th>
<th>P*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aplastic</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>vSAA/SAA</td>
<td>121</td>
<td>6.7</td>
<td>3.4-9.9</td>
<td></td>
</tr>
<tr>
<td>nSAA</td>
<td>21</td>
<td>5.9</td>
<td>4.4-7.8</td>
<td>.71</td>
</tr>
<tr>
<td>In remission</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Partial remission</td>
<td>8</td>
<td>6.6</td>
<td>2.8-10.4</td>
<td></td>
</tr>
<tr>
<td>Complete remission</td>
<td>6</td>
<td>9.2</td>
<td>3.5-14.9</td>
<td>.31</td>
</tr>
</tbody>
</table>

* Mann-Whitney test.
† In 13 patients serial assessments were performed. The total number of CAFC assays in the 31 patients was n = 47.
The pathogenesis of AA is still unknown. Several recent reports argue against a defective microenvironment and are in favor of a stem cell defect as the cause of AA. The frequencies of CD34+, CD33+, and CD34+CD33+ populations in BM of patients with AA are reduced as compared with normals. Growth of myeloid and erythroid colonies from separated AA CD34+ cells is decreased in comparison to normal CD34+ cells. Also in LTMC of AA BM, the production of nonadherent cells and CFU-GM is significantly reduced. Marsh et al have shown a defect of hematopoietic cell function with normally functioning stroma by crossover experiments inoculating nonadherent BM cells of AA patients onto preformed, irradiated normal stroma and vice versa. In these studies, the stage of differentiation at which the defect occurred remained unclear. The defect seen in LTMC might either be a consequence of absent or defective long-term culture-initiating cells (LTIC) or reflects an impaired differentiation of uncommitted to committed progenitor cells.

These studies indicate both a quantitative reduction of stem cells as well as a qualitative defect of early progenitor cells in AA. However, none of these studies measured quantitatively the number of CAFC or LTIC as an in vitro surrogate of long-term repopulating cells. Therefore, we have applied a human limiting dilution-type assay to the quantitative analysis of CAFC in AA. We inoculated BM-MNC of healthy controls or AA patients under limiting dilution conditions on preformed irradiated primary human stromal layers that were established from healthy human donors. To exclude a probable stroma effect, the limiting dilution analysis was performed on irradiated stroma layers established from normal donors. The irradiation did not affect the supportive stroma function in our system, which is in keeping with the findings of earlier reports. The use of primary human stromal layers is one of the major differences between our system and the human CAFC assay recently described by Breems et al, who used a murine preadipose stromal cell line FBMD-I. In contrast to Breems et al, who added IL-3 and G-CSF to their culture system, we did not add any exogenous growth factors to our culture system. With our limiting dilution CAFC assay, the mean CAFC frequency of 36 healthy donors was 84.4 per 10^6 BM-MNC, as determined at week 5 of culture. Breems et al reported a CAFC week-5 frequency of 44/10^6 BM-MNC in 8 normal BM samples. In an LTIC assay, Sutherland et al found a frequency of 37 LTIC per 10^6 percolled BM cells of 5 healthy controls. The differences in the experimental systems may account for the slight discrepancy between the frequencies reported.

The frequency of CAFC in BM-MNC of 31 patients with AA was reduced about 13-fold as compared with controls. To our knowledge, this is the first quantitative assessment of the hematopoietic defect in AA at the level of CAFC. A similar reduction of primitive progenitor cells was recently reported by Maciejewski et al using the LTIC assay. The longitudinal studies suggest that CAFC assays are not useful for prediction of possible therapy responses. The lack of correlation of CAFC with clinical characteristics (eg, severity or duration of disease and response to treatment) is in keeping with other studies that also failed to correlate in vitro growth of AA BM cells with clinical parameters.

Our results provide direct evidence that the hematopoietic defect in AA is present at the level of CAFC. However, there remain open questions. The nature of the defect is not clarified by our study. We cannot discriminate whether the reduced frequency of CAFC is due to an intrinsic stem cell defect (eg, a mutation in a gene regulating growth and differentiation) or is the consequence of extrinsic damage (eg, immune reaction towards progenitors at the CAFC level). There are many arguments supporting the view that immunemediated suppression of hematopoiesis is an important factor in the pathogenesis of AA. Nevertheless, attempts to show direct specific cytotoxic activity of T cells against autologous progenitor cells failed in most cases. One of several possible explanations for this failure relates to the use of inappropriate target cells. In the past, inhibitory effects of lymphocytes or lymphocyte-derived cytokines were monitored at the level of committed hematopoietic progenitor cells. However, this does not exclude an immune reaction directed against very early progenitor cells. The CAFC assay system provides the experimental tool to test this possibility.

Despite normal or near normal peripheral blood cell counts after response to immunosuppressive treatment, all AA patients in our study still had a low CAFC frequency. For estimating the total number of residual primitive progenitor cells in AA, one has to consider the marrow cellularity. Low CAFC frequency (per mononuclear cell) in remission patients means that the total residual number of CAFC is higher than in aplastic patients but lower than in normal controls. This finding is in accordance with the report that LTIC in patients who had hematopoietic recovery after treatment remained below the normal range in the majority of patients. Marsh et al reported that a marked defect of hematopoiesis in LTMC can be shown regardless of the degree of response to treatment. These results support the notion that most long-term survivors after immunosuppressive treatment are not really cured of their disease. Most of them exhibit persisting abnormalities, including subnormal peripheral blood counts, pathologic BM morphology, reduced frequency of CFU-GM, and reduced number of CD34+ cells.

It is not clear why AA patients achieve at least a partial response after treatment despite a persisting defect at the CAFC level. One can speculate that there are compensatory
mechanisms that lead to an expansion of more mature cells to maintain a normal or near normal peripheral blood count. This hypothesis is supported by the observation that the frequency of committed progenitors increased after response to immunosuppression, whereas frequencies of CAFC did not differ between aplastic and recovered AA patients. An alternative explanation is that in vivo stem cells are recruited into proliferation and differentiation by mechanisms that do not operate in LTMC. An overexpression of early and late-acting hematopoietic growth factors and inhibitory cytokines has been shown in AA. In vivo, all these factors might influence the proliferation of CAFC. The quantitative CAFC assay should make it possible to separately investigate the effects of these factors.

We conclude that the limiting dilution assay for CAFC permits a quantitative assessment of primitive progenitor cells in AA and other BM disorders. This assay system provides an in vitro approach to a number of relevant issues regarding the pathogenesis of AA. Effects of therapeutic agents (eg, hematopoietic growth factors) on the residual primitive progenitor cells in AA can be studied as well.

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