A
bstract. Marrow radioiron uptake and mar-
row blood flow were measured in order to evaluate iron
supply for erythropoiesis. Normal, phenylhydrazine-
treated and bled animals were studied. The plasma iron
turnover of seven normal rabbits was 1.49±0.22 mg/dl
whole blood per d. of 11 rabbits treated 4 d before with
phenylhydrazine was 5.16±1.81, and of four bled animals
the plasma iron turnover was 3.75±1.61. The cardiac
output and the percentage of blood flow to the marrow
was increased in phenylhydrazine-treated and bled ani-
mals. Marrow iron flow in phenylhydrazine-treated an-
imals was 38.3±32.6 μg/min per kg as compared with
control values of 7.0±1.3 (P < 0.01). This was due to an
increase in marrow flow, an increase in plasma iron, and
an increase in plasmocrit. In bled animals, in spite of
an increased marrow blood flow, marrow iron flow of
7.3±2.2 was similar to that of control animals due to a
lower plasma iron concentration. The calculated marrow
iron extraction of 3.7±2.4% in phenylhydrazine-treated animals was not different from that of control animals of 4.3±1.1, whereas extraction was increased in bled ani-
mals to 7.9±1.3 (P < 0.01). In additional studies of trans-
fused animals, acutely induced anemia was associated
with an increased cardiac output, but also with a relative
decrease in marrow flow, which left marrow iron supply
unaffected. It would appear from these studies that an
important mechanism for meeting the increased iron re-
quirement of the hyperplastic erythroid marrow is an
increase in marrow blood flow.

Introduction

Internal iron delivery is determined by the relation between
available iron supply and tissue requirements. Supply is rep-
resented by the amount of transferrin iron reaching the tissue
per unit time and by the degree of saturation of transferrin with
iron (1). Previous studies have emphasized the importance of
the amount of diferric transferrin present, since this complex
is capable of delivering much more iron than monoferric trans-
ferrin (2, 3). The total number of iron-containing transferrin
molecules vs. membrane receptor number is also important,
since iron uptake will be decreased if the number of iron-loaded
transferrin molecules is insufficient to saturate receptors. In ex-
amining these various relationships, it is essential to measure
blood flow, about which little is known.

Methods

New Zealand male rabbits weighing between 2.8 and 3.2 kg were main-
tained on a Purina rabbit chow diet (Ralston Purina Co., St. Louis,
MO). Some of these animals were studied in their basal state, and some
were studied 4 d after erythropoiesis had been stimulated by the intra-
venous injection of acetylpheynlhydrazine (30 mg/kg). Additional animals
were bled 10–20 ml/kg three to five times with replacement of plasma
during a 2-wk period before the study. Reticulocyte counts of normal
operated animals were 87±46 X 10^3/μl, of animals on the fourth day
after phenylhydrazine injections were 704±239, and of bled animals
were 585±123.

On the day of the experiment, animals were anesthetized by the
intramuscular injection of a 1:1 mixture of Vetalar (Parke Davis & Co.,
Morris Plains, NJ) and Rompun (Haver-Lockhart, Shawnee, KS) at a
dosage of 50 mg/kg and 10 mg/kg, respectively. Measurements were
made of plasma iron turnover (PIT) employing radioiron and of marrow
blood flow employing isotopically-labeled microspheres. At the end of
the experiment, animals were killed by exsanguination and the skin
and viscera were removed. The remaining carcass was autoclaved over-
night at a temperature of 130°C and a pressure of 1.4 kg/m^2. After that,
the individual bones were removed and cleaned. The prolonged autoclaving
softened the bones to the extent that they could be packed at the bottom
of plastic tubes.

The femurs of some animals were processed before autoclaving so
as to separate marrow from bone. The femurs were first cleaned of
surrounding tissues and then cut longitudinally using a small rotary
saw. Samples of cortical bone and of marrow were weighed and radio-
activity was determined. From the relative weight of bone vs. marrow
and their relative activities, the distribution of radioiron and of labeled
microspheres were determined. Less than 1% of radioiron in the femur
was found in the bone (0.98±0.1% in five normal animals and

1. Abbreviations used in this paper: CO, cardiac output; PIT, plasma
iron turnover.
circulating reticulocytes it was rapidly centrifuged with separation of red cells and plasma within 3 min of the time the sample was obtained. Blood samples at 10 min and at the approximate T½ were analyzed for plasma iron. When >90% of radioiron had disappeared from circulating plasma, animals were killed by exsanguination in saline perfusion over a 10–15-min period.

The effectiveness of perfusion in removing radioactivity due to labeled red blood cells was studied in three animals compared with three others in which perfusion was not carried out. The percentage of intravenously injected 55Fe-labeled red blood cells remaining in the skeleton, liver, and spleen in the nonperfused animals was 3.5±0.4, 9.6±2.2, and 0.3±0.1, and in the perfused animals was 0.3±0.1, 1.6±1.8, and 0.09±0.01, respectively. Accordingly, no correction was made for the 0.3% residual red cell activity in calculating the amount of radioiron localized in the skeleton.

Plasma iron turnover was calculated according to the formula previously described (9): PIT (mg/dl whole blood per day) = plasma iron (µg%) × (100-Hct × 0.9)/T½ (min) × 100. The plasma iron used in this formula was the extrapolated value at the T½ disappearance of radioiron (8). Red cell activity was determined from the counts per milliliter of washed red cells, the hematocrit, and the blood volume, which was assumed to be 58 ml/kg (mean value obtained in 10 normal animals). The iron supply to the erythroid marrow was calculated according to the following formula: marrow iron flow (µg/min per kg) = plasma iron (µg/dl) × marrow plasma flow (ml/min per kg). Plasma iron uptake by the bone marrow was calculated from the PIT and from the proportion of injected radioiron localized in the marrow at a time when 90% of radioactivity had left the plasma. Marrow iron uptake (mg/dl whole blood per day) = PIT (mg/dl whole blood per day) × marrow radioactivity (%). The percentage of iron extracted from plasma that circulated through the bone marrow was calculated from the iron uptake by the marrow divided by the iron flow through the marrow, according to the following formula: extraction (%) = marrow iron uptake (µg/min per kg) × 100/marrow iron flow (µg/min per kg). The rate of movement of erythrocytes into blood in animals with phenylhydrazine anemia was determined from changes in circulating red cell radioactivity after >90% of radioiron had disappeared from the plasma. Over a 2-h period, red cell activity increased by <5%. On the basis of this, it was not considered necessary in calculations of relative uptake by marrow and by blood to make corrections for that radioactivity which moved from marrow to blood during the study.

Statistical analysis. Nonparametric tests were employed: the Wilcoxon for paired values, the Mann-Whitney for unpaired values, and the Spearman rank correlation (10).

Results

Erythropoiesis in seven normal rabbits was characterized by ferrokinetic measurements (Table 1). These animals had a mean plasma iron of 155±27 µg/dl and a plasma iron turnover of 1.49±0.22 mg/dl whole blood/d. These values were similar to previous results (11), and there was the expected relationship between transferrin saturation and PIT (r = 0.71, P < 0.01). Mean erythron iron uptake in normal animals was 0.92 mg/dl whole blood/d of which 77% was in the marrow and 23% in the circulating blood. Mean cardiac output was 107 ml/min per kg, of which 6.4% went to the erythroid marrow. Only 4.3% of transferrin iron passing through the marrow cavity was extracted by the marrow.
Table I. Values of the Different Parameters of the Normal, Phenylhydrazine-treated, and Bleed Animals

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Normal (n = 7)</th>
<th>Phenylhydrazine-treated (n = 11)</th>
<th>Bleed (n = 4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hematocrit (%)</td>
<td>38±2</td>
<td>22±5*</td>
<td>21±3*</td>
</tr>
<tr>
<td>Plasma iron (μg/dl)</td>
<td>155±27</td>
<td>212±105*</td>
<td>68±27*</td>
</tr>
<tr>
<td>Transferin saturation (%)</td>
<td>57±12</td>
<td>63±28</td>
<td>18±8</td>
</tr>
<tr>
<td>T9 (min)</td>
<td>70±14</td>
<td>33±15*</td>
<td>15±2*</td>
</tr>
<tr>
<td>Total PIT (mg/dl whole blood/d)</td>
<td>1.49±0.22</td>
<td>5.61±1.81*</td>
<td>3.73±1.61*</td>
</tr>
<tr>
<td>Marrow uptake (mg/dl whole blood/d)</td>
<td>0.71±0.10</td>
<td>2.19±0.71*</td>
<td>1.45±0.63*</td>
</tr>
<tr>
<td>Blood uptake (mg/dl whole blood/d)</td>
<td>0.21±0.03</td>
<td>1.74±0.56*</td>
<td>1.16±0.50*</td>
</tr>
<tr>
<td>Cardiac output (ml/min/kg)</td>
<td>107±12</td>
<td>174±71*</td>
<td>153±50</td>
</tr>
<tr>
<td>Marrow flow (% of CO)</td>
<td>6.4±0.8</td>
<td>12.3±5.3*</td>
<td>8.6±1.1</td>
</tr>
<tr>
<td>Marrow Fe flow (μg/min/kg)</td>
<td>7.0±1.3</td>
<td>38.3±32.6*</td>
<td>7.3±2.2</td>
</tr>
<tr>
<td>Marrow Fe extraction (% of marrow iron flow)</td>
<td>4.3±1.1</td>
<td>3.7±2.4</td>
<td>7.9±1.3*</td>
</tr>
</tbody>
</table>

* P < 0.01 in relation to the values of normal animals using the Mann-Whitney test.

Similar studies were carried out in 11 animals with anemia produced by phenylhydrazine. Mean PIT was increased to 5.61 mg/dl whole blood/d. 44% of the erythron uptake of 3.39 mg/dl whole blood/d was in the circulating blood. CO was increased 62% and the proportion of blood flowing through the marrow increased by 92%. This increased flow along with the elevated plasma iron resulted in a more than fivefold increase in marrow iron flow. Percentage extraction of radioiron from blood circulating through the marrow was 3.7%.

Four bleed animals with the same degree of anemia had a PIT of 3.73 mg/dl whole blood/d, which was intermediate between normal and phenylhydrazine-treated animals. CO was increased 43% and the proportion of blood going to the marrow was also increased by 34%. Marrow iron flow was not different to the controls but the percentage extraction increased approximately twofold. In the 15 animals with increased erythropoiesis, iron taken up by the marrow was well correlated with PIT (r = 0.82, P < 0.001). Bone marrow flow showed a correlation with the PIT (r = 0.59, P < 0.01). No correlation was found between the degree of anemia and bone marrow blood or iron flow.

Because anemia itself might produce changes in marrow blood flow and iron extraction, an additional study was carried out in seven animals. Exchange transfusion lowered their hematocrit to 21±3%. PIT carried out before and immediately after exchange transfusion was not significantly affected, i.e., 2.1±0.9 mg/dl whole blood/d before and 2.1±0.9 afterward. CO was increased by 70%, but bone marrow flow was decreased by 38%, which left marrow iron flow essentially unchanged, i.e., 12.2±5.8 and 14.4±6.4 μg/kg per min. Marrow iron extraction was not significantly affected (4.6±1.8 vs. 4.0±3.3).

Discussion

In certain anemias associated with erythroid hyperplasia, there is evidence that a relative iron deficiency exists. The expected macrocytosis characteristic of the stimulated erythron may not be seen despite a normal plasma iron concentration, which suggests a limitation in hemoglobin production by the expanded population of erythroid precursors (12). Likewise, red cell protoporphyrin, an indicator of red cell iron deficiency, may increase when the production rises to over five times normal, despite a normal plasma iron or transferrin saturation (13), which indicates a relative deficiency in iron supply. The present studies were undertaken to examine iron flow to the marrow under normal conditions and with erythroid hyperplasia at different levels of plasma iron.

Rabbits were selected, since their iron kinetics had been studied in detail (11) and since the behavior of the transferrin receptor system closely resembled that of man (Huebers, H., and C. A. Finch, unpublished observations). By measuring the PIT and localization of radioiron in body tissues, it was possible to quantitate iron uptake, and more especially, the uptake of the erythroid marrow and of circulating reticulocytes. For measurement of CO, a microsphere technique was employed whereby the labeled spheres were injected by needle directly into the left side of the heart (14). The microsphere distribution was symmetrical on the two sides of the skeleton, which indicated a uniform distribution. Within the skeleton itself, some 85% of the microspheres were found in the marrow as compared with bone. These results in rabbits were similar to those reported in dogs by Gross et al. (7).

The cardiac output of 120±35 ml/min per kg in normal anesthetized animals was somewhat below that reported by Syfert and Boelkins (15) of 165±24 ml/min per kg in unanesthetized operated animals. The marrow flow of 10.7% of CO was similar to that described in other reports (7, 15). The iron marrow blood flow greatly exceeded marrow requirements for iron and a plasma iron extraction of 4.3% was calculated.

The production of hemolytic anemia by phenylhydrazine is associated with an initial destruction of ~20% of the circulating red cell mass each day (12). Proliferation of the erythroid marrow follows with a reticulocytosis in circulation and a rapid recovery of the hematocrit over a period of 7–10 d. The plasma iron is elevated and the transferrin is nearly saturated over the first 2–3 d and thereafter returns gradually to normal or subnormal levels. Our study was made on the fourth day, when anemia was severe and red cell proliferation marked, with a mean circulating reticulocyte count of eight times basal. A conspicuous finding was that the proportion of erythron radioiron taken up by circulating reticulocytes had doubled, i.e., an increase from 22% in normal animals to 44%. Thus, an increased proportion of radioiron uptake is independent of marrow flow. Actual mar-
row iron uptake was increased only three times. Nevertheless, marrow iron flow had increased more than fivefold, due to the increase in plasma iron concentration, in plasmatocrit, and in marrow blood flow. Thus, available iron increased in these animals more than did marrow requirements. The opposite situation occurred in four bled animals where iron supply was reduced while marrow requirements seemed increased. Comparing phenylhydrazine-treated and bled animals there is a considerably greater increase in PIT, in marrow iron uptake, and in reticulocyte output of the animals undergoing increased red cell breakdown. While there has been some question as to whether hemolysis in some special way augments erythropoiesis (16), it seems reasonable to explain the difference by the limited supply of iron. Not only is hemoglobin synthesis within the individual cell reduced when iron supply decreases, but there is also ample evidence that stem cell maturation is markedly curtailed in iron deficient anemia as compared with hemolytic anemia (17). That such an effect was demonstrated in bled animals when iron extraction was only 8% suggests that the capacity of the marrow to remove iron is limited. The increased blood flow to the marrow was helpful in balancing the increased marrow requirements. Previous studies with an isolated femur from phenylhydrazine-treated animals have also indicated an increased flow in this in vitro experimental setting (18). Thus, marrow flow would seem to behave similarly to the flow in other tissues and be regulated by metabolic activity. Obviously, other factors can influence blood flow, and it was of concern that anemia per se might have an influence on marrow flow as well as on erythropoiesis. CO has been observed by Richardson and Guyton (19) to increase in dogs whose hematocrits were rapidly lowered by blood exchange without volume exchange. However, our animals made acutely anemic by exchange transfusion with plasma showed no change in marrow iron supply, despite some immediate change in cardiac output. Thus, it was the increased erythropoiesis rather than the anemia that was responsible for increased marrow flow.

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References


