Adenine and Guanine Nucleotide Metabolism During Platelet Storage at 22°C

By C.M. Edenbrandt and S. Murphy

Adenine and guanine nucleotide metabolism of platelet concentrates (PCs) was studied during storage for transfusion at 22 ± 2°C over a 7-day period using high-pressure liquid chromatography. There was a steady decrease in platelet adenosine triphosphate (ATP) and adenosine diphosphate (ADP), which was balanced quantitatively by an increase in plasma hypoxanthine. As expected, ammonia accumulated along with hypoxanthine but at a far greater rate. A fall in platelet guanosine triphosphate (GTP) and guanosine diphosphate (GDP) paralleled the fall in ATP + ADP. When adenine was present in the primary anticoagulant, it was carried over into the PC and metabolized. ATP, GTP, total adenine nucleotides, and total guanine nucleotides declined more slowly in the presence of adenine than in its absence. With adenine, the increase in hypoxanthine concentration was more rapid and quantitatively balanced the decrease in adenine and platelet ATP + ADP. Plasma xanthine rose during storage but at a rate that exceeded the decline in GTP + GDP. When platelet ATP + ADP was labeled with 14C-adenine at the initiation of storage, half of the radioactivity was transferred to hypoxanthine (45%) and GTP + GDP + xanthine (5%) by the time storage was completed. The isotopic data were consistent with the presence of a radioactive (metabolic) and a nonradioactive (storage) pool of ATP + ADP at the initiation of storage with each pool contributing approximately equally to the decline in ATP + ADP during storage. The results suggested a continuing synthesis of GTP + GDP from ATP + ADP, explaining the slower rate of fall of GTP + GDP relative to the rate of rise of plasma xanthine. Throughout storage, platelets were able to incorporate 14C-hypoxanthine into both adenine and guanine nucleotides but at a rate that was only one fourth the rate of hypoxanthine accumulation. All of these data should be helpful in improving the function and viability of PC as currently stored for 5 days, in devising methods for storage beyond 5 days, and in the development of synthetic media for PC storage.

© 1990 by The American Society of Hematology.

Platelets are commonly stored for transfusion as 50-mL platelet concentrates (PCs) at 22 ± 2°C with constant agitation in autologous plasma. In the 1970s, platelets were stored in first-generation containers (such as Fenwal's PL-146; Deerfield, IL) constructed of plastics that had inadequate permeability to oxygen to meet the demands of the cells within. In such containers, lack of oxygen led to accelerated production of lactic acid, decreases in medium pH, and cell death when pH fell below 6.0. This often occurred within 3 days of storage. In currently used second-generation containers (such as Fenwal's PL-732), adequate oxygen penetration through the walls of the container minimizes production of lactic acid and medium pH is stable for 7 days. In such containers, in vivo viability, as judged by reinfusion of labeled platelets into normal volunteers, is reduced after 7 days of storage by approximately 35% relative to fresh platelets. Furthermore, there are distinct abnormalities of platelet function as assessed in vitro after storage.

The major cause (or causes) of such deterioration during storage is not known. One possibility would be failure of energy metabolism with depletion of metabolic adenosine triphosphate (ATP) and consequent deterioration of cellular function. Parallels could be drawn to storage of red cells. As early as 1947, Rapoport showed that red cell storage was accompanied by ATP breakdown to hypoxanthine. In 1962, Simon et al reported that the addition of adenine (750 µmol/L final concentration) at the initiation of storage increased ATP levels at the end of storage and improved postinfusion viability in vivo. Further studies showed that the added adenine was incorporated gradually into adenine nucleotides so that half of the original adenine remained after 6 weeks. With adenine supplementation, accumulation of hypoxanthine began earlier so that higher levels, approximately 200 µmol/L, were reached after 6 weeks of storage. Thus, there was evidence that ATP depletion played a role in loss of red blood cell viability during storage and that manipulation of the system by addition of adenine improved results.

There have been only a few studies of adenine nucleotide metabolism during PC storage and none of storage in "second generation" containers. Rao et al reported a fall in platelet ATP and ADP during 3 days of storage in "first generation" containers. Interpretation of such studies is complicated because Holmesen, Ireland, and Holmesen and Rozenberg have shown that there are at least two pools of adenine nucleotides in platelets. One pool, the cytoplasmic metabolic pool, rapidly incorporates 32P and 14C-adenine, whereas the storage pool, consisting of the granular content of ATP and ADP, is not labeled, at least in experiments performed over hours as opposed to days. The metabolic pool is thought to meet the platelet's ongoing metabolic needs, whereas the storage pool resides in dense granules that are secreted when the cell is stimulated by agonists. The meta-
Nucleotide metabolism during platelet storage 1885

The bolic pool has an ATP:ADP ratio of 8.1, whereas the storage pool ratio is 2:3. Because the depletion of ADP was relatively greater than ATP in the study by Rao et al., it was concluded that some of the depletion had to be from the storage pool.

In this study, we have examined adenine nucleotide metabolism during PC storage for 7 days in second-generation containers. Using a high-pressure liquid chromatography (HPLC) technique, we have been able to measure adenosine monophosphate, adenosine, and hypoxanthine, as well as ATP and ADP. The HPLC method also allowed us to measure guanosine triphosphate (GTP), guanosine diphosphate (GDP), and xanthine so that we could provide the first data on guanine nucleotide metabolism during PC storage as well.

Materials and Methods

Material. Perchloric acid (70%), potassium carbonate, ammonium phosphate, and ammonium hydroxide were obtained from Fisher Scientific (Fair Lawn, NJ). Cellulose filters, with a pore size of 0.45 μm, were from Millipore (Bedford, MA). Purine and pyrimidine bases, nucleosides, nucleotides, hexokinase (E.C.2.7.1.1.), myokinase (E.C.2.7.4.3.), xanthine oxidase (E.C.1.2.3.2.), purine nucleoside phosphorylase (E.C.2.4.2.1.), adenosine deaminase (E.C.3.5.4.4), guanase (E.C.3.5.4.3), 5'-nucleotidase (E.C.3.1.3.5.), and uricase (E.C.1.7.3.3.) were from Sigma (St Louis, MO). For the preparation of standard solutions, all purines and pyrimidines were individually dissolved in double-distilled water to a concentration of 30 mg/mL. The radiopharmaceutical purity of these compounds was checked by our HPLC system (see below) and found to be greater than 98% and 99%, respectively. Bio-HP, Scintiverse, liquid scintillation fluid was from Fisher Scientific.

Preparation of PC. Platelet-rich plasma (PRP) was prepared from blood obtained from human volunteers and anticoagulated with either citrate-phosphate-dextrose (CPD) or CPD-adenine (17.3 mg adenine/450 mL whole blood). PCs were prepared from PRP as previously described. The PC volume was so adjusted that the average volume during storage (considering sample volumes to be removed for study) would be 50 mL. PCs were stored in commercial grade storage bags for 3 days (PL-146) or 7 days (PL-732). As storage times, ratios of absorbance at 260 nm versus 280 nm, and 260 nm versus 230 nm. Peak identification was also performed by addition to the sample of a known amount of standard to demonstrate a quantitative increase in the height of a specific peak (spiking). Furthermore, specific enzymes (see above) were added to an aliquot of the sample that was buffered to an appropriate pH. The sample was incubated at 37°C for the required time and then rechromatographed. The disappearance of the substrate and the appearance of the appropriate reaction product confirmed both the identity and the purity of the chromatographic peak. Also, to identify a single peak in a sample, this peak was manually collected after chromatography, incubated with a specific enzyme, and rechromatographed. For quantitative measurements, peak heights were measured manually and compared with a standard curve for the correct compound. The standard curve (peak height vs concentration of purine compound) was constructed using commercial standards and was found to be linear (r > 0.997) for all compounds over the concentration range of interest in this study.

Ammonia measurement. Ammonia was measured using the ammonia enzymatic determination kit (Sigma).

Radiolabeling studies. [8-14C] adenine hydrochloride, 0.5 mL (25 μCi), was added at the initiation of storage to each of four PCs in PL-732 with CPD as the primary anticoagulant. Samples were drawn from all four PCs immediately after mixing, after 14 and 24 hours, and after 3, 5, and 7 days of storage. For radioactivity measurements, the injection volume of sample extract had to be increased to 75 μL to obtain sufficient counts above background in each peak. The eluent of each chromatographic peak was manually collected and mixed with 10 mL liquid scintillation fluid and counted in a liquid scintillation counter (Liquid Scintillation Spectrometer, Model 3320, Packard Instruments, Downers Grove, IL). From the data obtained for each chemical and radioactive, the specific activity of each purine compound was calculated. Unfortunately, the increased injection volume produced overlap between the
neighboring peaks, ATP and ADP, and GTP and GDP. Therefore, the radioactivity in ATP + ADP, and in GTP + GDP, are given as the sum of radioactivity of the two compounds.

To determine whether hypoxanthine could be incorporated into adenine and guanine nucleotides of platelets during storage (the salvage pathway), 3-mL samples were drawn from each of two PCs (PL-732, CPD) on days 0, 1, 3, 5, and 7 of storage. [8-14C]-hypoxanthine was added to each sample in an amount designed to achieve a specific activity of about 20 mCi/mmol of hypoxanthine immediately after mixing. The samples were incubated at 22°C for 4 hours in plastic tubes with intermittent agitation. Chemical amount and radioactivity of each purine compound were analyzed immediately after mixing and after 4 hours' incubation, as described above.

Statistical analysis. Rates of change during storage were determined as slopes of the "best fit" curve using simple linear regression. Rates of change were determined for both absolute concentrations and for concentrations expressed as percentage of the concentration at the start of storage. The latter procedure allowed greater sensitivity in detecting statistically significant differences, because for some variables such as adenine nucleotide content of fresh platelets there is considerable variation among normal individuals. The data were analyzed using unpaired and paired t-test and F-test after linear regression. Multiple regression was used with an interaction term to estimate the difference in the rate of concentration change of purine compounds between two groups. A difference was considered significant when \( P \leq 0.05 \). The data are given as mean ± SD unless otherwise stated.

Informed consent. All volunteers gave written, informed consent. The study was approved by the Institutional Review Board of Thomas Jefferson University.

RESULTS

Analysis of the HPLC system. The pH and ionic strength of the eluent was adjusted to give optimal resolution of ATP, ADP, AMP, GTP, GDP, hypoxanthine, and xanthine for quantitative analyses. This was achieved at the expense of the resolution of pyrimidine nucleotides, GMP, and inosine monophosphate (IMP). Adenine and guanine nucleotides were found only in platelets, ie, in extracted whole PCs and washed platelets but not in plasma from PCs. On the other hand, hypoxanthine, xanthine, and adenine were found only in plasma, ie, to the same extent in extracted PC and plasma from PC but not in washed platelets. No purine nucleoside was found in platelets or plasma. Guanine could not be detected and adenine was found only when included in the anticoagulant. Both GMP and IMP were identified in platelets but difficulties in resolving the two peaks from each other and from an interfering peak of an unknown plasma compound prohibited further quantitative analyses.

The detection limit (ie, peak height equal to 3 × baseline noise) was \( 5 \times 10^{-12} \) mol of purine compounds, allowing routine measurements of \( \geq 2 \) mmol for nucleosides and bases in plasma and >0.10 \( \mumol/10^{11} \) platelets for nucleotides. The absolute recoveries of hypoxanthine and adenine at two concentrations (10 \( \mumol/L \) and 100 \( \mumol/L \)) added to six samples of PC were 96.1% ± 4.0% and 92.2% ± 1.2% (mean ± coefficient of variation [CV]) for hypoxanthine, and 101.0% ± 6.8% and 91.1% ± 1.4% for adenine, respectively. The reproducibility of the method was assessed by analyzing 10 replicate samples extracted from the same fresh PC. Within-day precision was (CV) ATP 1.8%, ADP 2.2%, AMP 6.5%, GTP 2.5%, GDP 7.5%, hypoxanthine 2.9%, and xanthine 8.6%. Between-day precision of the method was assessed by analyzing the same fresh PC on five different days (CV): ATP 2.0%, ADP 2.6%, AMP 3.7%, GTP 2.2%, GDP 5.4%, hypoxanthine 2.4%, and xanthine 16.1%.

Characteristics of PC at the start of storage. Day 0 values of adenine and guanine nucleotides in platelets are given in Table 1. There were no significant differences when the two plastics and anticoagulants were compared. Hypoxanthine and xanthine concentrations in PC–plasma are also shown in Table 1. There was significantly more hypoxanthine in plasma from PCs when adenine was included in the anticoagulant (\( P < 0.05 \)) in both PL-732 and PL-146 containers. There was no significant difference in xanthine among the PCs.

Changes during storage. In the PCs studied, there was no significant change in platelet count during storage. pH did not fall below 6.9 during 7 days of storage in PL-732 or below 6.3 during 3 days of storage in PL-146. Mean platelet volume did not change during storage in PL-146 CPD-adenine or PL-732 with either anticoagulant, but increased by a mean of 20.5 ± 9.1% in PL-146 CPD. The latter is consistent with previous work, showing cellular swelling when pH fell to 6.5 to 6.7.

During PC storage, there was a steady decrease in platelet adenine and guanine nucleotides after the first 24 hours of storage (Fig 1). In CPD-adenine (Fig 1A), we found an increase of ATP (\( P < 0.05 \)) from days 0 to 1 in both PL-146 and PL-732. This was not observed with CPD. Continuous accumulation of hypoxanthine and xanthine was found in the

| Table 1. Day 0 Values of Adenine and Guanine Nucleotides in Platelets (\( \mumol/10^{11} \) platelets), and Hypoxanthine, Xanthine, and Adenine in Plasma (mol/L) |
|----------------------|-------|----------------------|-------|----------------------|-------|
|                     | PL-146-CPD | PL-146-CPD-Adenine | PL-732-CPD | PL-732-CPD-Adenine |
|----------------------|-------|----------------------|-------|----------------------|-------|
| ATP                  | 4.77 ± 0.82 | 4.79 ± 0.67 | 4.92 ± 0.35 | 5.24 ± 1.06 |
| ADP                  | 3.26 ± 0.96 | 3.14 ± 0.81 | 3.06 ± 0.41 | 3.00 ± 0.83 |
| AMP                  | 0.30 ± 0.05 | 0.30 ± 0.07 | 0.32 ± 0.05 | 0.31 ± 0.07 |
| GTP                  | 0.72 ± 0.07 | 0.69 ± 0.15 | 0.75 ± 0.06 | 0.73 ± 0.22 |
| GDP                  | 0.50 ± 0.10 | 0.50 ± 0.14 | 0.57 ± 0.13 | 0.60 ± 0.22 |
| Hypoxanthine         | 6.7 ± 3.1 | 22.3 ± 7.3 | 4.7 ± 3.6 | 21.0 ± 13.0 |
| Xanthine             | 1.80 ± 2.30 | 3.55 ± 2.98 | 2.78 ± 2.73 | 3.10 ± 3.20 |
| Adenine              | ND     | 215.6 ± 24.1 | ND     | 228.8 ± 17.6 |

Values are means ± SD. Abbreviation: ND, not detectable.
supernatant plasma. To allow quantitative comparison between the rates of decline of adenine and guanine nucleotides in platelets, which are expressed in μmol/10^11 platelets, and the rates of increase of hypoxanthine and xanthine in plasma, which are expressed in μmol/L, we used the platelet concentration of each bag to convert the adenine and guanine nucleotide concentrations to μmol/L. Table 2 gives these rates of change and indicates which are significantly different from zero. When CPD was the primary anticoagulant, the rate of decrease of total adenine nucleotides was balanced quantitatively by the rate of increase in hypoxanthine. In CPD-adenine, adenine continuously decreased and the accumulation of hypoxanthine was augmented twofold to threefold relative to CPD (P < .01 for both PL-146 and PL-732). The sum of the decrease in adenine nucleotides and adenine balanced quantitatively the increase of hypoxanthine. Xanthine accumulated in all four PC groups with no statistically significant difference among them. In all four groups, the rate of decrease of total guanine nucleotides was somewhat less than the rate of increase in xanthine. Adenine consumption and hypoxanthine and xanthine accumulation were not found when PFP was stored as a control.

Table 2. Rates of Change per Day of Purine Compounds During PC Storage for Three Days in PL-146 and Seven Days in PL-732 Using Either CPD or CPDA as Anticoagulant

<table>
<thead>
<tr>
<th></th>
<th>PL-146</th>
<th>PL-732</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CPD</td>
<td>CPDA</td>
</tr>
<tr>
<td>ATP</td>
<td>-4.6 ± 2.4*</td>
<td>-1.6 ± 3.1†</td>
</tr>
<tr>
<td>ADP</td>
<td>-3.2 ± 3.3*</td>
<td>-3.7 ± 2.5*</td>
</tr>
<tr>
<td>AMP</td>
<td>0.0 ± 0.2†</td>
<td>0.0 ± 0.2†</td>
</tr>
<tr>
<td>Total AN</td>
<td>-7.8 ± 5.6*</td>
<td>-5.2 ± 5.3†</td>
</tr>
<tr>
<td>Adenine</td>
<td>ND</td>
<td>-13.9 ± 4.2*</td>
</tr>
<tr>
<td>Hypoxanthine</td>
<td>-9.0 ± 2.0†</td>
<td>19.3 ± 2.4*</td>
</tr>
<tr>
<td>GTP</td>
<td>-1.2 ± 0.2*</td>
<td>-0.8 ± 0.4†</td>
</tr>
<tr>
<td>GDP</td>
<td>-0.3 ± 0.3†</td>
<td>-0.1 ± 0.5†</td>
</tr>
<tr>
<td>Total GN</td>
<td>-1.5 ± 0.5*</td>
<td>-0.9 ± 0.9§</td>
</tr>
<tr>
<td>Xanthine</td>
<td>2.2 ± 0.6†</td>
<td>1.7 ± 0.6†</td>
</tr>
</tbody>
</table>

Values of intracellular nucleotides are expressed as μmol/L of PC rather than on a per cell basis as in Table 1. This allows a direct, quantitative comparison between the rates of change of intracellular nucleotides and extracellular adenine, hypoxanthine, and xanthine, which are also expressed as μmol/L of PC. Values are means ± SD. P values reflect significance relative to a zero rate of change. n = 4 for all groups except PL-732 CPDA, where n = 5.

*P < .001.
†P > .05.
§P < .01.
§P < .05.
The four groups of PCs were compared regarding the rates of change in concentration of adenine and guanine nucleotides during storage. We found no significant difference for any of the compounds when comparing PL-732 CPD with PL-146 CPD and PL-732 CPD-adenine with PL-146 CPD-adenine. However, in PL-732, significant differences were found between CPD and CPD-adenine. In CPD-adenine, there was a significantly lower rate of decrease of ATP, GTP, ATP + ADP + AMP, and GTP + GDP. These differences in PL-146 were not statistically significant.

Role of contaminating leukocytes. In the studies designed to determine the role of leukocytes in the changes observed, there was a significant difference on day 0 between LD PCs and LE PCs in ATP (LD 4.48 ± 0.40 μmol/10¹¹ platelets v LE 5.82 ± 0.47 μmol/10¹¹ platelets; P < .001); ADP (LD 2.63 ± 0.26 μmol/10¹¹ platelets v LE 3.16 ± 0.29 μmol/10¹¹ platelets; P < .01); and GTP (LD 0.58 ± 0.09 μmol/10¹¹ platelets v LE 0.72 ± 0.08 μmol/10¹¹ platelets; P < .05). The increased values for LE PC undoubtedly reflect the presence of ATP, ADP, and GTP in leukocytes. There were no significant differences on day 0 between LD PC and LN PC or between LN PC and LE PC. During 7 days of storage, there was no significant difference among the preparations in the rates of change of purine nucleotides or their metabolites, indicating that the changes described in the previous section were due to platelet metabolism.

Ammonia production. There was pronounced ammonia production during 7 days of storage. In PL-732 with CPD as anticoagulant, levels (mmol/L) were 0.31 ± 0.04, 0.63 ± 0.01, and 0.75 ± 0.03 on days 1, 4, and 7, respectively. There was no significant difference between LD PC and LE PC in the rate of ammonia accumulation. There was much less ammonia production when PFP was stored as a control with levels (mmol/L), 0.07 ± 0.01, 0.15 ± 0.03, and 0.22 ± 0.03 on days 1, 4, and 7, respectively.

Studies with ¹⁴C-adenine labeling. When ¹⁴C-adenine was added to fresh CPD PC, it was incorporated into purine nucleotides and their metabolites so that no ¹⁴C-adenine was detectable after 14 hours. Therefore, 14 hours was taken as the initial (day 0) measurement of radioactivity in these compounds. Separation of stored PC into platelets and plasma showed the cells to contain all the ¹⁴C-labeled adenine and guanine nucleotides and no radioactive nucleosides and bases, whereas the plasma contained radioactive hypoxanthine and xanthine. The final amount of adenine nucleotides formed from ¹⁴C-adenine was approximately 0.3 μmol/10¹¹ platelets, a level too low to produce a measurable increase of ATP + ADP. The sums of radioactivity in the samples investigated from days 0 to 7 did not differ significantly from the radioactivity of the ¹⁴C-adenine originally added, suggesting that the substances under study were the main purine metabolites and indicating that no radioactivity was unaccounted for during the time of investigation.

After the initial labeling at 14 hours, there was continuous decrease of radioactivity in ATP + ADP over the next 7 days accompanied by an increase of radioactivity in hypoxanthine (Fig 2A). The chemical amount of ATP + ADP decreased by about 35% during this period (-0.40 ± 0.06 μmol/10¹¹ platelets on day 7).
platelets per day; \( P < .001 \)), whereas the radioactivity of ATP + ADP decreased by about 50% (−2,263 ± 270 counts per minute (cpm)/d; \( P < .001 \)). Thus, there was a decrease in specific activity of ATP + ADP during storage of about 23% (−126 ± 64 cpm/\( \mu \)mol/d; \( P < .001 \)), indicating that radioactive ATP + ADP was being preferentially degraded (Fig 2C). The specific activity of hypoxanthine was always higher than the specific activity of ATP + ADP and it too decreased during storage (Fig 2C).

Radioactivity was also incorporated into AMP, but it represented only 0.6 ± 0.3% of the total radioactivity. The specific activity of AMP was 745 ± 216 cpm/\( \mu \)mol at the start of storage, far less than that of ATP + ADP (3,669 ± 744 cpm/\( \mu \)mol). Radioactivity in AMP did not change significantly during storage. Because the chemical amount of AMP decreased slightly (−0.019 ± 0.004 \( \mu \)mol/10^11 platelets/d; \( P < .001 \)), its specific activity showed a minor increase (−40 ± 18 cpm/\( \mu \)mol/d; \( P < .05 \)).

Radioactivity was slowly distributed into guanine nucleotides increasing by 123 ± 26 cpm/d (\( P < .001 \)) (Fig 2B). However, this radioactivity was less than 5% of the total. The specific activity of GTP + GDP increased continuously during storage (351 ± 36 cpm/\( \mu \)mol/d; \( P < .001 \)) and did not differ significantly from that of ATP + ADP on day 7. Total radioactivity in xanthine increased continuously as well during storage (153 ± 27 cpm/d; \( P < .001 \)), but the slight increase in its specific activity was not statistically significant. Because the specific activity of GTP + GDP was always higher and increased faster than that of xanthine, it is likely that the \( ^{14} \)C-labeled adenine was first incorporated into GTP + GDP and later degraded together with nonradioactive GTP + GDP to xanthine.

Studies with \( ^{14} \)C-hypoxanthine. \( ^{14} \)C-labeled hypoxanthine was added to 3-mL samples withdrawn on days 0, 1, 3, 5, and 7 from two PCs (PL-732, CPD). Taking into account the steady production of hypoxanthine in PC during storage, the amount of radio-labeled hypoxanthine added was adjusted to attempt to achieve as constant a specific activity of hypoxanthine as possible immediately after mixing. This approach was reasonably successful, because the mean specific activity of hypoxanthine for the five samples immediately after mixing was 42.8 ± 12.5 and 43.7 ± 2.8 cpm/\( \mu \)mol in each of the two studies. During the 4-hour incubations of these aliquots, radioactivity was incorporated into adenine and guanine nucleotides and xanthine. The total amount of radioactivity in the peaks analyzed after the 4-hour incubations did not differ significantly from the amount of radioactivity initially added to the two PCs. Thus, no radioactive loss was noted during the incubation, suggesting that the main \( ^{14} \)C-hypoxanthine metabolites were studied.

The rates of incorporation of \( ^{14} \)C-hypoxanthine into adenine and guanine nucleotides were calculated from the radioactivity measured in ATP + ADP + AMP and GTP + GDP, respectively, and from the mean specific activity of hypoxanthine during the incubation time. The uptake rate into adenine nucleotides was 41.3 ± 7.0 and 51.5 ± 14.0 nmol/10^11 platelets per 4 hours in each of the two PCs, equivalent to a utilization of plasma hypoxanthine of 5.5 ± 0.9 and 4.9 ± 1.3 \( \mu \)mol/L/d. The mean hypoxanthine accumulations in these two PCs were 20.2 \( \mu \)mol/L and 21.4 \( \mu \)mol/L/d. Therefore, about 25% of the net production of hypoxanthine was reincorporated. The rate of \( ^{14} \)C-hypoxanthine incorporation into guanine nucleotides was 5.1 ± 1.6 and 6.3 ± 2.7 \( \mu \)mol/10^11 platelets per 4 hours, respectively, ie, about one tenth of the uptake rate into adenine nucleotides. There was no significant difference in uptake rate between the two PCs or between different days of storage for either guanine or adenine nucleotides. Radioactivity was also found in xanthine after the 4-hour incubation, demonstrating the further degradation of radioactive guanine nucleotides to that compound.

DISCUSSION

Using our HPLC technique, we found results for adenine and guanine nucleotides in fresh PC (Table 1) that were similar to previous reports.\(^{11,17-22}\) Reported concentrations of hypoxanthine and xanthine in plasma vary widely (0.4 to 7 \( \mu \)mol/L and 0.4 to 5 \( \mu \)mol/L, respectively.\(^{24-33}\) It has been shown that if plasma and blood cells are not separated immediately after phlebotomy, hypoxanthine and xanthine will continue to be formed in vitro.\(^{7,13,14}\) Several hours are required for the preparation of fresh PC so that our plasma and cell samples were separated for analysis about 3 to 4 hours after blood collection. This, no doubt, explains our somewhat higher values compared with the literature. The higher values of hypoxanthine in PC with adenine are undoubtedly due to an increased rate of hypoxanthine formation during this 3- to 4-hour period, similar to that observed during the subsequent week of storage (Fig 1).

The studies of PC derived from blood anticoagulated with CPD demonstrate a continuing decline in adenine nucleotide content in both PL-146 and PL-732 containers. There was a 20% reduction in both ATP and ADP after 3 days of storage. This is in contrast to the report of Rao et al.,\(^4\) who found both a larger reduction of adenine nucleotides (−27.1% for ATP and −39.1% for ADP) and a greater reduction in ADP than in ATP. We have no definite explanation for these differences, although Rao et al used different techniques: luciferin-luciferase assay of ethanol extracts of platelets. However, because 90% or more of platelet ADP is in the storage pool, our results are consistent with their conclusion that some of the nucleotide depletion during PC storage was from the storage pool.

After 7 days of storage in PL-732 with CPD as primary anticoagulant, platelet adenine nucleotides had decreased to approximately 60% of day 0 values. Plasma hypoxanthine levels rose at the same rate at which adenine nucleotides fell (Table 2), strongly suggesting that the latter were being converted to hypoxanthine quantitatively, either by deamination of AMP in the metabolic pool to IMP with further metabolism to hypoxanthine or by release from the storage pool with conversion to hypoxanthine by plasma enzymes. Figure 3 depicts these two possibilities schematically. When adenine was present in the primary anticoagulant, it was carried over into the PC so that its concentration at the start of storage was approximately 220 \( \mu \)mol/L. During PC storage, the concentration of adenine decreased gradually so that approximately two thirds had been consumed after 7
are formed from the adenine nucleotide pool, presumably through it can be readily incorporated into the adenine nucleotide pool.

The oval represents the cell wall. Amounts of ATP, ADP, IMP, and subsequently degraded to xanthine. If adenine is present hypoxanthine phosphoribosyl-transferase reaction. GTP and GDP are drawn to scale. Adenine nucleotides from both hypoxanthine already formed. During the 7 days of these isotopic studies, chemical ATP + ADP decreased by about one third. The isotopic measurements were consistent with the initially labeled and unlabeled pools each contributing approximately equally to this decrease, ie, degradation of half of the labeled pool and one fourth of the unlabeled pool. This would result in the 25% decrease in the specific activity of ATP + ADP that was observed.

The observation that the specific activity of AMP was only 20% of that of ATP + ADP in fresh platelets is new. Some authors have assumed that 14C-adenine distributes evenly among ATP, ADP, and AMP in the metabolic pool and that all AMP is in this pool. If this were true, the specific activity of AMP would be higher than that of ADP and ATP because of the nonradioactive ADP and ATP in the storage pool. Our findings point to a more complex pattern of distribution of 14C-adenine among the adenine nucleotides and suggest a
NUCLEOTIDE METABOLISM DURING PLATELET STORAGE

sizable pool of AMP that is not in isotopic equilibrium with metabolically active ATP and ADP.

These are the first studies to examine guanine nucleotides during PC storage. They play a major role in many cell functions, such as the synthesis of adenine nucleotides from IMP by the purine salvage pathway and the initiation of platelet aggregation and release by the phosphoinositide pathway. Therefore, deficiencies may be important. As for adenine nucleotides, guanine nucleotides showed a gradual reduction to 60% of control values after 7 days. As GTP and GDP decreased, plasma xanthine increased, but at a greater rate. The steady increase of radioactivity in GTP, GDP, and xanthine found in the 14C-adenosine labeling studies indicate a continuous flow of adenine nucleotides to AMP, IMP, and GTP + GDP with subsequent degradation to xanthine (Fig 3). Similar labeling was also demonstrated in the 14C-hypoxanthine experiments. This shuttle of purines from adenine nucleotides and hypoxanthine to guanine nucleotides and xanthine explains the greater increase in xanthine during storage relative to the decrease in total guanine nucleotides. This part of purine metabolism has not been shown for platelets previously.

Platelets are not able to synthesize purine nucleotides de novo. However, hypoxanthine may be salvaged by hypoxanthine phosphoribosyl-transferase to form IMP, which can then be converted to AMP and GMP (Fig 3). Jerushalmy et al. and Rivard et al. demonstrated hypoxanthine incorporation into purine nucleotides of fresh, washed platelets incubated at 37°C. In the present study, hypoxanthine was incorporated into nucleotides at a rate of approximately 50 nmol/4 h/1011 platelets. This pathway remained intact during 7 days of PC storage. In accord with the two earlier studies, 90% and 10% of the hypoxanthine were incorporated into adenine and guanine nucleotides, respectively. Because we measured both the rate of purine nucleotide degradation to hypoxanthine and the rate of hypoxanthine incorporation into purine nucleotides, we were able to show that as much as 25% of the net production of hypoxanthine could be reincorporated through the salvage pathway.

There are several possible causes for the adenine nucleotide degradation that occurs during PC storage. Our studies provide information about platelet adenine and guanine nucleotide metabolism over a period of time equivalent to the platelet life span. They may be providing insight into normal platelet physiology, suggesting that adenine nucleotide depletion occurs with in vivo aging. On the other hand, it may simply be that as ATP is used for the cell’s baseline needs, it cannot be resynthesized rapidly enough because the conditions of storage are metabolically unfavorable. Under these circumstances, AMP would accumulate and be degraded to hypoxanthine. This metabolic depletion might permit leakage of storage pool nucleotides. On the other hand, during storage, platelets may be intermittently stimulated to secrete granule contents because of agitation and contact with the plastic walls of the container. We know that α-granular contents such as β-thromboglobulin appear in supernatant plasma during storage. There is evidence that secretion by fresh platelets is accompanied by degradation of metabolic ATP to hypoxanthine. Recently, it was shown that addition of inhibitors of platelet function such as theophylline and prostaglandin E1 to PC during storage improved maintenance of platelet morphologic integrity and ATP levels. In these studies, there was strong correlation between ATP levels and measurements that reflect morphologic integrity, which in turn have correlated with in vivo viability in the past. Certainly further understanding of the mechanisms of nucleotide depletion and the relationship between this depletion and other measurements reflecting cellular integrity should allow us to improve the quality of platelets during and after storage.

REFERENCES

18. Holmsen H, Storm E, Day HJ: Determination of ATP and


34. Simon TL, Nelson EJ, Murphy S: Extension of platelet concentrate storage to 7 days in second-generation bags. Transfusion 27:6, 1987


40. Zoran K, Jerance D, Brkljac O: The role of glutamine oxidation and the purine nucleotide cycle for adaptation of tumour energetics to the transition from the anaerobic to the aerobic state. Biochem J 252:381, 1988


43. Rivard GE, McLaren JD, Brunst RF: Incorporation of hypoxanthine into adenine and guanine nucleotides by human platelets. Biochim Biophys Acta 381:144, 1975


Adenine and guanine nucleotide metabolism during platelet storage at 22 degrees C

CM Edenbrandt and S Murphy