Long Term Effects of Radiation on T and B Lymphocytes in Peripheral Blood of Patients with Hodgkin's Disease

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ABSTRACT Total lymphocyte counts, and the percentage of T and B lymphocytes and monocytes in untreated patients with Hodgkin's disease were not significantly different from those observed in normal donors. At the completion of radiotherapy, the mean total lymphocyte count of 503/mm³ was 4 SD below the mean for normal controls. Although a group of 26 patients in continuous complete remission from 12 to 111 mo after radiation treatment regained normal total numbers of lymphocytes and monocytes, they exhibited a striking T lymphocytopenia and B lymphocytosis. Concomitantly, there was a significant increase of null (neither T nor B) lymphocytes.

The response of peripheral blood lymphocytes to phytohemagglutinin, concanavalin A, and tetanus toxoid before treatment was significantly impaired. 1–10 yr after completion of treatment there seemed to be little or no recovery of these responses. The capacity of peripheral blood lymphocytes to respond to allo-antigens on foreign lymphocytes in vitro (mixed lymphocyte reaction) was normal in nine untreated patients. However, the mixed lymphocyte reaction was markedly impaired during the first 2 yr after treatment. There was a partial and progressive restoration of the mixed lymphocyte reaction during the next 3 yr, and normal responses were observed in patients in continuous complete remission for 5 yr or more. The in vivo response to dinitrochlorobenzene was also examined. 88% (15/17) of patients initially sensitive to dinitrochlorobenzene were anergic to the allergen at the completion of a course of radiotherapy, but nine of these regained their hypersensitivity response during the 1st yr after treatment.

This data suggests that there is a sustained alteration in both the number and function of circulating T cells after radiation therapy in patients with Hodgkin's disease which may persist for as long as 10 yr after treatment. The restoration of cell mediated immune functions after radiotherapy is time dependent and its kinetics may differ for various T-cell functions. The implications of these findings with respect to the state of immunological competence after radiotherapy are discussed.

INTRODUCTION

Radiation induced alterations in the number and function of peripheral blood lymphocytes have recently been described in patients treated with radiotherapy for carcinoma of the breast (1–6), lung (7–9), bladder (7–10), uterine cervix (2, 6, 11), testicular seminoma and carcinoma (12, 13), Hodgkin's disease, (14–19) and in children receiving prophylactic craniospinal irradiation for acute lymphoblastic leukemia (13, 20). Most studies have demonstrated an acute lymphocytopenia and suppression of immune function, shortly after the initiation of treatment. Several investigators have shown that a partial recovery may occur within the first 18 mo after the completion of treatment (6, 8, 10–14). There are, however, few data available on the long term effects of radiation therapy on the number and immune function of peripheral blood lymphocytes in patients in continuous remission many years after treatment.

In the present study, we describe long term changes in the number, cell surface characteristics, and in vitro function of peripheral blood lymphocytes in a group of patients in continuous complete remission after an intensive course of radiation therapy for Hodgkin's disease.

METHODS

Patient selection and staging. The study comprised a group of 227 patients with Hodgkin's disease referred to
Stanford University Medical Center between 1965 and 1975. The histologic diagnosis of the initial biopsy specimens was confirmed and classified according to the Rye modification (21) of the Lukes and Butler classification (22). The patients were thoroughly evaluated for extent of disease before therapy as has been detailed elsewhere (23, 24) and staged according to the scheme proposed at the Ann Arbor Conference (25).

The immunological studies were performed in two groups of patients. The first consisted of 148 untreated patients, in whom studies were performed after initial biopsy but before any staging procedures. All but a few of these patients (those with stage IV disease) were eventually staged with bipedal lymphangiography and laparotomy with splenectomy. 8 patients had pathological stage IA, 2, stage IB, 54, stage IIA, 16, stage IIIB, 32, stage IIIA, 15, stage IIIB, 14, stage IV A, and, 8, stage IV B disease.

The second group consisted of 79 treated patients (18 patients had stage IA, I, IB, 33, IIA, 6, IIB, 14, IIIA, 5, IIIB, 1, IVA, and, I, IVB). At the time of the immunological studies, all tested patients were in continuous complete remission from 1–10 yr after the initial course of treatment. All patients were treated initially with intensive radiotherapy delivered by a 6 MeV linear accelerator employing techniques of local, extended field, or total lymphoid irradiation as previously described (24). 10 of the patients also received prophylactic multiple drug (MOPP) chemotherapy after irradiation (26).

In addition, 86 normal persons, consisting of laboratory personnel, physicians, and nurses, roughly similar in age and sex distribution to the patients with Hodgkin’s disease, were tested.

Lymphocyte separation. Peripheral blood was collected in heparin and lymphocytes were separated on a Ficoll-Hypaque gradient as previously described (27).

Identification and enumeration of T and B lymphocytes and monocytes. T lymphocytes were identified by a complement-dependent antibody cytotoxicity assay according to Bobrove et al. (28). This method utilizes an anti-T-cell serum developed by immunizing an adult goat with viable human thymus cells, and subsequent absorption of the crude antiserum with malignant B cells. The percentage of cells killed by the antiserum was determined by trypsin blue exclusion. T lymphocytes were also identified on the same blood samples by their ability to form spontaneous rosettes with sheep erythrocytes (E rosettes), by using the method of Bentwich et al. (29). At least 200 cells were counted, and each test was done in triplicate. Only lymphocytes with at least three erythrocytes attached were considered E rosettes.

B lymphocytes were identified by staining the Ig-bearing cells with a fluorescein-conjugated polyvalent rabbit anti-human-Ig-antiserum (28). Monocyte contamination was determined by staining with alpha-naphthol acetate (Sigma Chemical Co., St. Louis, Mo.) according to Yam et al. (30). The percent monocyte contamination and the cytotoxic index obtained with the anti-T-cell serum were used to calculate the percentage of T cells in the peripheral blood as follows:

\[
\% \text{T cells} = \frac{\text{cytotoxic index (IC₅₀)}}{\text{100 - IC₅₀ monocyte contamination}} \times 100
\]

The percentage of B cells was independent of the monocyte contamination, since only small cells were examined for surface Ig staining, thereby excluding monocytes (28).

These procedures were performed immediately after Ficoll-Hypaque purification of freshly drawn blood. However, in some cases the same tests were repeated after incubation of the cell suspensions in RPMI-1640 and 20% fetal calf serum for 18–24 h at 37°C in a humidified atmosphere of 5% CO₂ in air. The survival of the cells after incubation, determined by cell counts, was greater than 90%. The percentage of viable cells as determined by trypan blue exclusion was greater than 98%.

The absolute numbers of T and B lymphocytes in the peripheral blood were calculated by multiplying the percentage of T and B lymphocytes by the absolute lymphocyte count computed from the total leukocyte and differential counts obtained on the same day (31).

Mixed lymphocyte reactions. The ability of lymphocytes to respond to alloantigens in vitro was tested by a one-way mixed lymphocyte culture microassay according to Sasazuki et al. (32). In brief, 50,000 Ficoll-Hypaque purified peripheral blood lymphocytes from normal individuals or patients were mixed with 50,000 Ficoll-Hypaque purified stimulator cells from unrelated normal donors or patients with Hodgkin’s disease. Stimulator cells were inactivated by radiation, receiving a single dose of 6,000 rads from a radioactive cesium¹³⁷ source (Mark I model 25 Irradiator, J. L. Shepherd and Associates, Glendale, Calif.) in air at room temperature. Cells were then mixed in 0.2 ml of RPMI-1640 medium with 25 mM Hepes buffer supplemented with L-glutamine, streptomycin, penicillin, and 10% heat inactivated human AB serum, in round bottom microtiter trays (Linbro Chemical Co., Inc., New Haven, Conn.). The mixtures were cultured for 6 days at 37°C in a humidified atmosphere containing 5% CO₂, and subsequently pulsed with 1 μCi [³H]thymidine (2 Ci/mmol, Schwarz-Mann Radiochemicals, Rockville, Md.) for 16 h. The rate of DNA synthesis was estimated by measurement of the incorporation of the radioactive thymidine into the responder cells.

Tenata toxoid induced transformation of lymphocytes. The lymphocyte response to a specific antigen was investigated by mixing 10 μg of tetanus toxoid with Ficoll-Hypaque purified peripheral blood lymphocytes in 0.2 ml of RPMI-1640 medium with 25 mM Hepes buffer supplemented with L-glutamine, streptomycin, penicillin, and 10% heat inactivated human AB serum, in flat bottom microtiter trays. The cells were cultured for 6 days and pulsed with [³H]thymidine for 16 h as described above. Except where otherwise stated, 200,000 cells were used per culture.

Stimulation of lymphocytes by lectins. Blastogenic stimulation of peripheral blood lymphocytes by phytohemagglutinin (PHA, Wellcome Reagents Ltd., Beckenham, England) and concanavalin A (Con A, crystallized X3 and lyophilized, Miles Laboratories, Inc., Kanakee, Ill.) was tested according to the method of Levy and Kaplan (33). This microassay measures the degree of stimulation of protein synthesis by lectins (PHA, Con A) by comparing the increase of [³H]leucine incorporation obtained at various concentrations of the mitogen with the amount of incorporation by unstimulated cells. The degree of stimulation of protein synthesis (stimulation ratio) was expressed in terms.

Abbreviations used in this paper: Con A, concanavalin A; DNBC, dinitrochlorobenzene; Ig, immunoglobulin; MLC, mixed lymphocyte reaction (culture); MOPP, multiple drug chemotherapy with nitrogen mustard, oncovin, prednisone, and procarbazine; PBL, peripheral blood lymphocytes; PHA, phytohemagglutinin; TLI, total lymphoid irradiation.

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of the ratio of counts incorporated in the presence of the
mitogen to the counts incorporated simultaneously in the
saline control.

Delayed hypersensitivity to DNBC. Patients were tested
for their ability to develop delayed hypersensitivity skin
reactions to 2,4-dinitrochlorobenzene (DNBC) before stag-
ing laparotomy or therapy. In the majority of cases, sensi-
tization was performed with 500 μg DNBC as previously
described (34); an early subgroup of 34 patients was sensi-
tized with 2,000 μg DNBC. Challenge was performed 10–14
days later with 100 μg of the chemical applied to the skin
of the opposite forearm. A reaction was considered positive
if both erythema and induration developed with or without
vesiculation 24–96 h after challenge. In 66 patients, repeated
challenges were also performed after completion of treat-
ment at 3–6 mo intervals for 1–10 yr, until a positive re-
response was observed.

RESULTS

Absolute lymphocyte counts. Table I summarizes the
mean lymphocyte counts of 22 normal donors, 61 pa-
tients with untreated Hodgkin's disease, and 26 patients
with treated Hodgkin's disease in continuous long term
complete remission. The mean total lymphocyte count in
the group of treated patients was not significantly dif-
ferent from the mean counts of normal donors or of pa-
tients with untreated Hodgkin's disease. All patients
in the treated group had received radiation therapy 12–111 mo before testing, and three patients had also
received six courses of MOPP chemotherapy (Table II).

Absolute lymphocytopenia, defined as values more
than 2 SD below the mean for normal donors, (mean±
SD = 2,038±295 lymphocytes/mm³) was observed in
the present study in 24/61 (39%) of the patients with
untreated Hodgkin's disease. At the completion of radio-
therapy, all patients manifested severe lymphocytopenia
(Table II). The mean count for this group was 503
lymphocytes/mm³ and all patients had values more than
4 SD below the mean for normal donors. By 12–111 mo
after completion of radiation treatment, only 7/26
(27%) had absolute lymphocytopenia. There was, how-
ever, no correlation between pretreatment lymphocyto-
penia and that observed 12–111 mo later. Only three
patients in whom lymphocytopenia was observed before
treatment also had absolute lymphocytopenia 21, 55, and
60 mo after completion of treatment. The other four pa-
tients with posttreatment lymphocytopenia had normal
counts before treatment; conversely, eight other patients
with pretreatment lymphocytopenia had normal lympho-
cyte values 12–111 mo after radiation. There was also
no correlation between either the treatment modality
employed or the duration of continuous complete remis-
sion and the presence of absolute lymphocytopenia (Ta-
ble II).

B lymphocyte counts. Tables I and II show a sum-
mary of the results of quantitation of B cells identified
as surface Ig-bearing cells. The mean percentage of Igbear-
ning cells in normal donors was 20% of the total
lymphocytes (Table I), and the mean absolute B lym-
phocyte count±SD was 407±101. Although the mean
percentage of Ig-bearing cells in patients with untreated

| Table I |

| T and B Lymphocytes in Normal Donors and Patients with Hodgkin's Disease |

<table>
<thead>
<tr>
<th>Cells from Ficoll-Hypaque gradients</th>
<th>Peripheral blood cells</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Percent</td>
</tr>
<tr>
<td></td>
<td>monocytes</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>%</td>
</tr>
<tr>
<td>Normal donors (22 patients)</td>
<td>17±1.2</td>
</tr>
<tr>
<td>Untreated Hodgkin's disease</td>
<td>18±1.4</td>
</tr>
<tr>
<td>Untreated Hodgkin's disease</td>
<td>27±3.7</td>
</tr>
<tr>
<td>Hodgkin's disease treated and</td>
<td>20±3.1</td>
</tr>
<tr>
<td>no evidence disease (26 patients)</td>
<td>(0–72)</td>
</tr>
</tbody>
</table>

* Calculated values; those for total lymphocytes are derived by multiplying the total leukocyte count by the percentage of lymphocytes in the differential count; those for T and B lymphocytes by multiplying the total lymphocyte count by the measured percentages of T and B lymphocytes, respectively. Data on these normal donors and on 42 of the untreated patients (20 Stage II, 22 Stages III and IV) have been previously published (31).
† Mean±SE (Range).
‡ Calculated from cytotoxic index.
Hodgkin's disease was not significantly different from the percentage in normal donors, the mean absolute B lymphocyte count was significantly lower \((P < 0.05)\) that that of normal donors (Table I). Of the 61 patients with untreated Hodgkin's disease 23 (38%) had absolute B lymphocytopenia, defined as counts more than 2 SD below the mean for normal donors. Immediately after completion of radiotherapy, there was a severe depletion of peripheral blood B lymphocytes in five patients tested \((mean \pm SD = 47.2 \pm 31.3 \text{ B lymphocytes/mm}^3)\). At 12–111 mo after radiotherapy, both the mean percentage and the mean absolute number of B lymphocytes were significantly higher \((P < 0.01)\) than those observed in normal donors. Of the 26 treated patients, 16 (61%) had an absolute B lymphocytosis and only one had an absolute B lymphocytopenia (Table II). The degree of B lymphocytosis was, however, mild and the highest count observed was 1,526 B lymphocytes/mm\(^3\).

**T lymphocyte counts.** The mean T lymphocyte count \(\pm SD\) in 22 normal donors as detected by the cytotoxicity assay was 1,600 \(\pm 303\). There was no significant difference between the mean of the untreated patients and that of the normal controls (Table I), although 20/61 (33%) of the untreated patients had an absolute T lymphocytopenia. Nearly all patients with T lymphocytopenia had an associated B lymphocytopenia and absolute total lymphocytopenia. There was a striking T lymphocytopenia in five patients tested immediately after radiotherapy \((mean \pm SD = 150.2 \pm 134.2)\) and also in the group of 26 patients tested 12–111 mo after completion of treatment (Table I, II). The mean T lymphocyte count of 793 lymphocytes/mm\(^3\) (Table I) for the latter group was significantly lower than the mean value for normal donors \((P < 0.01)\). Absolute T lymphocytopenia occurred in 19/26 (73%) of the patients in this group.

In the treated patients, there was no correlation between the presence of T lymphocytopenia and either the treatment technique employed or the time interval from completion of treatment (Table II). Even patients

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**Table II**

<table>
<thead>
<tr>
<th>Type</th>
<th>Initial stage</th>
<th>Total lymphocytes per mm(^3) before XRT</th>
<th>TLI*</th>
<th>Total lymphocytes per mm(^3) at XRT completion</th>
<th>Months after XRT</th>
<th>Cell from Ficoll-Hypaque gradients</th>
<th>Lymphocytes</th>
<th>Peripheral blood cells</th>
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<tr>
<td></td>
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<td></td>
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<td>E-rosettes</td>
<td>Cytoxic index</td>
<td>Monocytes</td>
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<tr>
<td>NSHD</td>
<td>IA</td>
<td>1,239</td>
<td>TLI</td>
<td>686</td>
<td>55</td>
<td>42</td>
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<td>10</td>
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<td>1,946</td>
<td>TLI</td>
<td>216</td>
<td>61</td>
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<td>Mantle</td>
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<td>47</td>
<td>76</td>
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<td>TLI</td>
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<td>12</td>
<td>12</td>
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<td>25</td>
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<td>697</td>
<td>13</td>
<td>37</td>
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<td>572</td>
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<td>33</td>
<td>26</td>
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<td>TLI</td>
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<td>37</td>
<td>26</td>
<td>37</td>
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<td>1,495</td>
<td>TLI + MOPP</td>
<td>576</td>
<td>30</td>
<td>42</td>
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<td>26</td>
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<tr>
<td>NSHD</td>
<td>IIA</td>
<td>1,500</td>
<td>Mantle</td>
<td>294</td>
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<td>44</td>
<td>53</td>
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<tr>
<td>NSHD</td>
<td>IIA</td>
<td>2,000</td>
<td>TLI</td>
<td>216</td>
<td>49</td>
<td>35</td>
<td>12</td>
<td>18</td>
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<tr>
<td>NSHD</td>
<td>IIA</td>
<td>4,066</td>
<td>TLI</td>
<td>845</td>
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<td>38</td>
<td>21</td>
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<tr>
<td>NSHD</td>
<td>IIA</td>
<td>972</td>
<td>TLI</td>
<td>498</td>
<td>55</td>
<td>33</td>
<td>38</td>
<td>7</td>
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<tr>
<td>NSHD</td>
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<td>2,040</td>
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<td>786</td>
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<td>46</td>
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<td>944</td>
<td>TLI</td>
<td>780</td>
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<td>50</td>
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<td>MCHD</td>
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<td>1,914</td>
<td>UP ABD</td>
<td>435</td>
<td>62</td>
<td>35</td>
<td>20</td>
<td>34</td>
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<td>IIA</td>
<td>1,560</td>
<td>TLI</td>
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<td>83</td>
<td>38</td>
<td>17</td>
<td>2</td>
</tr>
<tr>
<td>HD</td>
<td>IIB</td>
<td>815</td>
<td>TLI</td>
<td>ND</td>
<td>88</td>
<td>48</td>
<td>43</td>
<td>25</td>
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<tr>
<td>NSHD</td>
<td>IIEA</td>
<td>2,325</td>
<td>TLI</td>
<td>468</td>
<td>104</td>
<td>43</td>
<td>32</td>
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<tr>
<td>HD</td>
<td>IIA</td>
<td>2,106</td>
<td>TLI</td>
<td>ND</td>
<td>111</td>
<td>45</td>
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<tr>
<td>MCHD</td>
<td>IIIB</td>
<td>864</td>
<td>TLI + (\text{(^{198}\text{Au})})</td>
<td>252</td>
<td>20</td>
<td>48</td>
<td>47</td>
<td>14</td>
</tr>
<tr>
<td>NSHD</td>
<td>IIIEB</td>
<td>960</td>
<td>TLI + MOPP</td>
<td>280</td>
<td>22</td>
<td>27</td>
<td>27</td>
<td>10</td>
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<tr>
<td>MCHD</td>
<td>IIIB</td>
<td>2,940</td>
<td>TLI + (\text{(^{198}\text{Au})})</td>
<td>980</td>
<td>36</td>
<td>41</td>
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<td>0</td>
</tr>
<tr>
<td>NSHD</td>
<td>IIIB</td>
<td>1,330</td>
<td>TLI + MOPP</td>
<td>ND</td>
<td>42</td>
<td>30</td>
<td>39</td>
<td>16</td>
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<tr>
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<td>IIB</td>
<td>1,710</td>
<td>TLI + (\text{(^{198}\text{Au})})</td>
<td>640</td>
<td>56</td>
<td>22</td>
<td>10</td>
<td>72</td>
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<tr>
<td>NSHD</td>
<td>IIB</td>
<td>968</td>
<td>TLI + (\text{(^{198}\text{Au})})</td>
<td>350</td>
<td>60</td>
<td>36</td>
<td>38</td>
<td>8</td>
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<tr>
<td>NSHD</td>
<td>IIB</td>
<td>1,920</td>
<td>TLI + (\text{(^{198}\text{Au})})</td>
<td>108</td>
<td>101</td>
<td>41</td>
<td>31</td>
<td>30</td>
</tr>
</tbody>
</table>

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* Mantle, mantle field irradiation only; \(^{198}\text{Au}\), intravenous colloidal radioactive gold; HD, Hodgkin's disease; LPHD, lymphocyte predominance HD; MCHD, mixed cellularity HD; NSHD, nodular sclerosing HD; XRT, radiotherapy.
† Calculated from cytotoxicity index.
treated more than 8 yr previously had absolute T lymphocytopenia.

Incidence of "null" lymphocytes. "Null" cells are defined as cells, identified morphologically as small lymphocytes, which do not carry surface markers of either B lymphocytes or T lymphocytes. Examination of the frequency distributions of "null" lymphocytes shows that more than 90% of the normal donors and patients with untreated Hodgkin's disease had \(<14\%\) "null" lymphocytes, whereas 59% of the treated patients in long term remission had 15–49% "null" lymphocytes. There was no correlation between the presence of an increased percentage of "null" lymphocytes and the interval from completion of radiotherapy (Table II).

Percentage of monocytes. Table I shows a summary of the percentages of monocytes contaminating the Ficoll-Hypaque gradients. There were no statistically significant differences among the percentages of monocytes in gradient-separated cells from the peripheral blood of normal donors, patients with untreated Hodgkin's disease, or patients in long term remission after radiotherapy.

T lymphocytes by E rosette method. Confirming our earlier observations in a smaller number of patients (31), the mean percentage of T lymphocytes identified by the E rosette test in untreated patients (52.3%) was significantly lower (\(P<0.05\)) than the percentage detected by the cytotoxicity assay (62.4%) (Table III). In contrast, the mean percentage of T cells detected by the E rosette method in the group of patients in long term continuous remission after radiotherapy was significantly higher (\(P<0.05\)) than the percentage determined by the cytotoxicity assay (Tables I, II, III). The percentage of T lymphocytes in the treated patients was significantly lower by both methods than the corresponding percentages for normal donors and untreated patients.

Effect of overnight incubation on T cell determination. Incubation of peripheral blood lymphocytes from patients with untreated Hodgkin's disease in medium containing 20% fetal calf serum is followed by restoration of the percentage of E rosette forming cells up to the levels of T lymphocytes detected by the cytotoxic antibody assay (Table III). Incubation of Ficoll-Hypaque purified peripheral blood lymphocytes from treated patients for 24 h in 20% fetal calf serum did not change the percentage of E rosette forming cells, but significantly increased the percentage of T lymphocytes detected by the cytotoxicity assay from 30.6±5.5 to 42.6±4.3% (Table III). Even after incubation in fetal calf serum, the percentage of T lymphocytes by either method remained significantly lower (\(P<0.01\)) than the corresponding values observed in normal donors and in patients with untreated Hodgkin's disease.

Effect of overnight incubation on Ig-bearing cells. It has recently been shown that fluoresceinated whole rabbit anti-human-Ig-antiserum used to detect surface immunoglobulins on lymphocytes stains both cells producing immunoglobulins endogenously as well as cells binding immunoglobulin via the Fc receptor (35, 36). Staining of the latter cells can be reduced after overnight incubation in 20% fetal calf serum.

Incubation of Ficoll-purified lymphocytes from 12 normal donors for 24 h in RPMI-1640 plus 20% fetal calf serum resulted in a decrease of the mean percentage of Ig-bearing cells from 18.2 to 11.7 (Table III). Similar incubation of Ficoll-purified lymphocytes from 12 treated patients resulted in a reduction of the mean per-

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**Table III**

**Percentage of T Lymphocytes by Spontaneous E-Rosette and Cytotoxicity Assays and Percentage of Ig Bearing Lymphocytes (B-cells) in Ficoll-Hypaque Purified Peripheral Blood Lymphocytes of Normal Donors and of Patients with Hodgkin's Disease Before and After 24 h Incubation in RPMI-1640 with 20% Fetal Calf Serum**

<table>
<thead>
<tr>
<th>Group</th>
<th>E-rosettes*</th>
<th>Cytolysis*</th>
<th>Ig bearing cells*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Before incubation</td>
<td>After incubation</td>
<td>Before incubation</td>
</tr>
<tr>
<td></td>
<td>Before incubation</td>
<td>After incubation</td>
<td>Before incubation</td>
</tr>
<tr>
<td>Normal donors</td>
<td>66.1±0.9</td>
<td>65.4±1.2</td>
<td>68.3±2.8</td>
</tr>
<tr>
<td>(56–81) (40 donors)</td>
<td>(38–82) (22 donors)</td>
<td></td>
<td>(9–29) (12 donors)</td>
</tr>
<tr>
<td>Untreated Hodgkin's disease</td>
<td>52.3±1.5</td>
<td>64.0±1.3</td>
<td>62.4±2.4</td>
</tr>
<tr>
<td>(26–82) (57 patients)</td>
<td>(43–83) (34 patients)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hodgkin's disease treated and no evidence of disease</td>
<td>36.2±1.8</td>
<td>36.8±1.7</td>
<td>30.6±5.5</td>
</tr>
</tbody>
</table>

* Mean±SE (Range).
centage of Ig-bearing cells from 42.7 to 26.4. These differences after overnight incubation were both statistically significant ($P < 0.01$).

**Lymphocyte stimulation by PHA.** Fig. 1 summarizes the results of PHA stimulation assays with Ficoll-Hypaque purified lymphocytes obtained from normal donors and from patients with untreated and treated Hodgkin's disease. Optimal stimulation in normal donors occurred at a PHA concentration of 2.5 µg/ml (mean stimulation ratio±SE = 4.45±0.2) and a sharp decrease was observed at higher or lower concentrations. Confirming an earlier report (33), the present study shows that the mean stimulation ratio in 132 patients with untreated Hodgkin's disease was significantly lower than the normal values at all dose levels between 0.25 and 10 µg/ml of PHA (at each dose tested, $P < 0.01$). The decrease in responsiveness to PHA was significantly more pronounced in untreated patients with advanced disease (stages III and IV) than in patients with stages I and II (data not shown). However, even in the latter group, the response was significantly below that of normal donors.

The response to PHA of peripheral blood lymphocytes from 66 radiation-treated patients tested while in long term complete remission is also presented in Fig. 1. The stimulation ratios over a wide range of PHA concentrations were even more profoundly depressed than those for the untreated patients ($P < 0.01$). There was no correlation between the time interval from completion of treatment and the response to PHA. Patients treated as much as 9–10 yr earlier had a mean stimulation ratio (2.39±0.39) similar to that of patients treated only 1 yr before PHA stimulation (2.03±0.28). There was also no correlation between the extent or topographical localization of the radiation fields and response to PHA. For example, the mean stimulation ratio (1.78±0.20) in patients given only infradiaphragmatic irradiation was as low as that in patients given TLI. No additional suppression was induced by the adjunctive administration of MOPP chemotherapy.

**Lymphocyte stimulation by Con A.** Patients with untreated Hodgkin's disease had a decreased response to Con A (Fig. 2) which was significant ($P < 0.01$) at concentrations of 5 and 10 µg/ml. A nearly identical degree of suppression was observed in a group of 19 patients previously treated with radiation and in continuous complete long term remission.

**Lymphocyte stimulation by tetanus toxoid.** Fig. 3 shows the response of peripheral blood lymphocytes from normal donors and patients with Hodgkin's disease to in vitro stimulation by tetanus toxoid (kindly supplied by the Department of Public Health of the Commonwealth of Massachusetts). None of the tested individuals (normal donors or patients with Hodgkin's disease) had received an injection of the toxoid shortly before in vitro testing. It was assumed that all tested individuals had been actively immunized against tetanus sometime in the past, although not all individuals could recall such an event.

As shown in Fig. 3, culture of peripheral blood lymphocytes from normal donors with tetanus toxoid resulted in a significant blastogenic response. Of 40 normal donors tested, 34 (85%) showed activities of the extracted DNA exceeding 20,000 cpm per well (background counts of unstimulated cells did not exceed 1,000
cpm/well). In contrast, only 3/9 (33%) of the untreated patients ($P < 0.01$) exhibited positive in vitro responses to the tetanus toxoid.

The degree of in vitro stimulation of 200,000 lymphocytes from treated patients was compared with that of 100,000 cells from normal individuals (Fig. 3), since the number of peripheral blood lymphocytes identifiable as T cells is reduced by approximately 50% after therapy. The degree of stimulation of normal individual lymphocytes under these conditions was still significantly higher than that of the treated patients. A further increase in the number of tested lymphocytes from treated patients to 400,000 did not result in a significant increase in the response to tetanus toxoid (Fig. 3) which remained significantly lower than the response of 200,000 cells from normal donors.

**Mixed lymphocyte reaction (MLR).** The capacity of peripheral blood lymphocytes from normal donors and patients with Hodgkin’s disease to respond to foreign lymphocytes in vitro is shown in Fig. 4. In the present study, MLR tests resulting in extracted DNA activities greater than 10,000 cpm per well were defined as positive responses, since this was the lower limit of normal responses. It should be noted that only 12/131 (9%) of the normal unrelated combinations showed activities between 10,000 and 20,000 cpm per well. These were arbitrarily defined as weakly positive responses whereas activities higher than 20,000 cpm per well were defined as strongly positive responses.

Cells from nine untreated patients with active Hodgkin’s disease (3 patients in stage IA, 2 IIA, 2 IIB, 1 IIIA, and 1 patient in stage IIIB disease) and from 12 patients in long term remission after radiotherapy were found to induce positive responses in 24/26 (92%) random combinations with responder cells from unrelated normal individuals (Fig. 4). It should be noted, however, that 5/9 (55%) of the responses, using untreated patients as donors of stimulator cells, were either subnormal or weakly positive, whereas only 3/17 (18%) of the responses, using stimulator cells from treated patients in complete remission, were weak.

Peripheral blood lymphocytes from patients with untreated Hodgkin’s disease were found to respond adequately when stimulated by either normal donor cells or cells obtained from other patients with Hodgkin’s disease. In 20/21 (95%) random combinations positive MLR responses were observed (Fig. 4). Recent radiotherapy (which in all cases was TLI) significantly reduced the capacity of patients with Hodgkin’s disease to respond to the MLR test. Eight patients tested 12–30 mo after treatment showed adequate responses in only 4/12 (33%) combinations when randomly paired with...
normal donor lymphocytes, and in 4/16 (25%) when paired with lymphocytes from other treated patients. In contrast, of 37 combinations in which responder cells were used from patients treated 31 to 120 mo previously, and stimulator cells from unrelated normal donors or other treated patients, 35 (95%) yielded positive responses. Fig. 5 shows the correlation between responses observed in treated patients and the time elapsing from completion of radiotherapy. The MLR was significantly impaired during the first 2 yr after treatment. There was a partial and progressive restoration of the response during the next 2 yr. and normal responses were observed in patient in continuous complete remission for 5 yr or more.

**Delayed hypersensitivity reaction to topical application of DNCB.** A previous report from this institution described the impairment of delayed hypersensitivity reactions to topical application of DNCB in patients with untreated Hodgkin's disease of all stages (37). Only 27% of untreated patients responded to challenge with 100 µg of DNCB as compared to 84% of normal individuals. A similar impairment was observed in untreated patients in the present study. Only 36/112 (32%) of the untreated patients in all stages of disease responded to challenge with DNCB. There was no correlation between the absolute number of peripheral blood T lymphocytes, the in vitro response to PHA, and in vivo reactivity to DNCB (Table IV).

In 69 patients, the response to challenge with 100 µg DNCB was tested both before treatment and at 3–6 mo intervals after treatment until a positive reaction became apparent. Of 17 patients who demonstrated a positive response before treatment, 15 (88%) were found to be anergic to DNCB immediately after completion of radiotherapy. Nine of the latter regained their capacity to respond to the chemical 4–12 mo after treatment and another patient did so 40 mo after radiotherapy. However, five patients (29%) did not regain their ability to respond to DNCB during a period of up to 8 yr after completion of treatment (Table V).

**TABLE V**

**Delayed Hypersensitivity Response to DNCB before and after Treatment in Patients with Hodgkin's Disease: Patients were Sensitized with 500–2,000 µg DNCB before Treatment and Challenged with 100 µg 10-14 Days Later and at 3-6 mo Interval after Completion of Treatment**

<table>
<thead>
<tr>
<th>Before treatment</th>
<th>%</th>
<th>After treatment</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pos*</td>
<td>17/69 (25)</td>
<td>Pos 12/17 (71)</td>
<td></td>
</tr>
<tr>
<td>Neg†</td>
<td>52/69 (75)</td>
<td>Neg 40/52 (77)</td>
<td></td>
</tr>
</tbody>
</table>

* Pos, Positive delayed hypersensitivity response to DNCB.
† Neg, No delayed hypersensitivity response to DNCB.

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**DISCUSSION**

Most of the reported studies on the effects of ionizing radiation on immune functions in mammals have dealt with single, whole body radiation exposures (38, 39). There have been only a few studies on the effects of localized or regional fractionated irradiation, such as employed in clinical radiotherapy, on immune functions in man. In this study, we have described some of the acute and chronic changes in the number and functions of T and B lymphocytes occurring after TLI of patients with Hodgkin's disease.

Before radiotherapy, the total lymphocyte counts and
the percentage of B cells, T cells, and monocytes were not significantly different from those observed in normal donors. However, at the completion of treatment, the mean total lymphocyte count of 503/mm³ was 4 SD below the mean for normal controls. Acute lymphocytopenia after a course of radiation has been described in a variety of clinical situations involving localized or extended field radiotherapy (1–20). Recovery usually begins shortly after completion of treatment (6, 7, 12), and continues through the next 1–2 yr. In the present series of treated patients, total lymphocyte counts were restored to pretreatment levels in less than 2 yr. However, there were sustained alterations in the relative frequencies of the various subclasses of lymphocytes with a striking inversion of the normal T vs. B lymphocyte ratio. The percentage of T cells by either E rosette method or the cytotoxicity assay was very low, while the percentage of Ig-bearing cells was significantly increased (Tables I, II). Furthermore, when the combined percentage of T and B lymphocytes was computed, there was a significantly increased percentage of “null” lymphocytes in the treated patients. These changes persisted as long as 8–10 yr in some patients.

Engeset et al. (16) have described an increased percentage of Ig-bearing lymphocytes in 6 out of 7 patients tested 5–36 mo after completion of total lymphoid irradiation for Hodgkin’s disease. Cohnen et al. (40) noted a normal percentage of Ig-bearing lymphocytes in four untreated patients with Hodgkin’s disease, while the percentage in two other patients treated with radiation and chemotherapy was significantly increased. A postradiotherapy increase in the percentage of complement receptor lymphocytes has also been reported in 40 patients with carcinoma of the breast (1).

Our study suggested that in the acute phase, during fractionated irradiation, there is a severe depletion of the pool of circulating lymphocytes, but after the completion of treatment, there is a gradual restoration of this pool possibly by B-cell precursors originating in the unirradiated bone marrow. The process of restoration seems to be complete by the 1st yr, but for unknown reasons the level of B cells continues to rise for many years, resulting in an “overshoot” in the absolute numbers of B lymphocytes in the circulating pool. This may be a compensatory rise related to the prolonged T lymphocytopenia.

The Ig-bearing cells (B cells) identified in the present study may have acquired surface immunoglobulin either by endogenous production or by binding of exogenous immunoglobulin via Fc receptor. To identify only those B cells with endogenously produced surface immunoglobulin, lymphocytes were incubated in vitro for 12 or more h in fetal calf serum at 37°C before staining for surface Ig (35, 36). Incubated lymphocytes from both normal donors and treated patients showed significant decreases in the percentage of Ig-bearing cells. However, the mean percentage of Ig-bearing cells in treated patients (26.4%) was still more than twofold higher than that in the normal donors (11.7%) (Table III). It is still possible that the increased percentages of Ig-bearing cells postincubation do not represent only B cells, but are partially due to specific antibodies directed against cell surface components of cells other than B cells, which are not removed during the overnight incubation.

Diminished percentages and total numbers of peripheral blood T lymphocytes have previously been reported in patients receiving radiation for carcinoma of the breast (1, 6) and Hodgkin’s disease (19, 41). The relative and absolute T lymphocytopenia described in the present report are striking because of the magnitude and the persistence of the changes. Severe depletion of T lymphocytes postirradiation was detected by both the cytotoxicity and the E rosette assays. We have recently reported (31), and have confirmed (Table III) that in untreated patients with Hodgkin’s disease, the percentage of T lymphocytes by the E rosette assay is significantly lower than that detected by the cytotoxicity assay. However, this functional impairment is reversed by overnight incubation of the lymphocytes in medium containing 20% fetal calf serum, with restoration of the percentage of E rosette-forming cells up to the level detected by the cytotoxicity assay. In contrast, overnight incubation of Ficoll-purified lymphocytes from treated patients in 20% fetal calf serum resulted in no significant change in the percentage of E rosette-forming cell. This suggests that, in contrast to untreated patients, the low percentage of E rosettes observed after radiation therapy reflects a true depletion of T lymphocytes in the peripheral blood.

The nature of the increased population of “null” lymphocytes in treated patients is still unknown. It is not clear whether they represent immature forms of B cells, T cells, or both. It appears, however, that they do not belong to the monocyte group since they did not react in the staining procedure for nonspecific esterases with alpha-naphthol-acetate.

The extensive changes in the numbers of circulating B and T lymphocytes during and after a course of fractionated radiation are also accompanied by functional sequelae. A radiation induced decrease in the response of peripheral blood lymphocytes to PHA has been reported by other investigators in patients receiving various forms of radiotherapy for malignant diseases (2–4, 8–12).

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T and B Cells in Hodgkin’s Disease
The finding that peripheral blood lymphocytes from patients with untreated Hodgkin's disease react normally when used as a source of responder cells in the MLR test (Fig. 4) is consistent with other reports in the literature (44, 45). After total lymphoid irradiation, there was a marked reduction of the ability of the peripheral blood lymphocytes to respond in the MLR reaction (Fig. 5). This persisted for at least 2 yr after irradiation, but a partial and progressive recovery occurred during the 3rd through the 5th yr after treatment. Normal MLR responses are observed in most patients in complete remission for 5 yr or more.

A similar pattern of recovery from radiation damage exists for the delayed hypersensitivity response to DNCB, in those patients who were sensitive to the allergen before TLI. It is also of interest that some patients who were anergic to DNCB before treatment became reactive to the allergen after radiotherapy (Table V). It is conceivable that the repeated challenges with 100 µg of DNCB served to sensitize such patients after their disease had been eradicated. It has been shown that a single application of 100 µg DNCB can induce delayed hypersensitivity in 19% of normal individuals (34, 37). An alternative hypothesis is that sensitization to the chemical did indeed occur before treatment despite the fact that Hodgkin's disease activity prevented the normal response to challenge, and that a population of specific memory precursors which survived in these patients throughout irradiation later provided effector cells for the hypersensitivity response after active disease had been eradicated. The recovery of the response in these patients is considerably slower than that of patients who show hypersensitivity to DNCB before radiotherapy.

The recovery from radiation damage observed for the hypersensitivity response to DNCB and for the MLR test is in marked contrast to the lack of recovery of the responses to PHA and Con A which persists for at least 10 yr. It is possible that the differences in the kinetics of recovery of the different tests reflect differences in both the nature of the mitogenic stimulus and in the in vitro assays, since the MLR response was measured by H³ TdR uptake and the PHA and Con A response by [¹⁴C]leucine uptake. The initial general elimination of T-cell functions correlates with the depletion of the pool of circulating T cells during a course of radiotherapy. The slow rates of postradiation recovery of these functions suggest that the process of T-cell maturation may be impaired after total lymphoid irradiation. Some subsets of partially differentiated lymphocytes may fail to complete the normal thymus-dependent sequence of morphological and functional maturation due to the lack of thymic influence caused by normal age-dependent thymic involution and by irradiation. Other factors

6, 8–10, 12–14). In the present series the levels of stimulation of peripheral blood lymphocytes by PHA were significantly lower in treated patients than in patients with untreated Hodgkin's disease, although the responsiveness in the latter group was significantly reduced as compared to normal individuals (Fig. 1). The mechanism of the impaired response to PHA in the treated and untreated groups may be different, since the number of T cells in the peripheral blood of treated patients is significantly reduced as compared to that in untreated patients. It is likely that intensive extended field or total lymphoid irradiation contributes to the decreased response to PHA by eliminating subsets of T cells capable of responding to PHA. If so, our data indicate that there is little, if any, restoration of this subpopulation in the circulating pool during the first 10 yr after therapy. On the other hand, the impaired response in untreated patients appears to be due to a factor which interferes with the capacity of the circulating lymphocytes to form E rosettes and to respond adequately to PHA. We have recently been able to demonstrate such a factor in the serum and in extracts from the spleens of untreated patients with Hodgkin's disease, and to reverse the impaired responses of peripheral blood lymphocytes from these patients by overnight incubation in 20% fetal calf serum.

Lymphocyte stimulation by Con A was also impaired in both untreated patients and in patients in long term remission after radiotherapy (Fig. 2). However, the degree of impairment of the Con A response in the two groups of patients was not significantly different, in contrast to the PHA responses. The possibility that different subpopulations of T lymphocytes may be involved in the response to these two mitogens, as has been suggested by studies in rodents (42), may account for the difference in the levels of stimulation induced by PHA and Con A in treated patients in the present study.

The in vitro proliferative response to recall antigens, such as tetanus toxoid, and to allogeneic lymphocytes seems to be specific to T cells alone, even when examined in long term (6 day) cultures (43). The suppressed response to tetanus toxoid in untreated patients is probably related to altered T-cell function since these patients generally do not have T lymphocytopenia (31). However, after radiation, the decreased response could well be attributable to both decrease in number and impairment of function of T cells, since increasing the number of tested cells from treated patients from 200–000 to 400,000 did not restore their response (Fig. 5).

such as splenectomy, destruction of the normal matrix of lymph nodes by radiation, and perhaps the production of specific anti-T-antibodies may also participate in the process of maturation arrest. Variations of the initial radiosensitivity of different subpopulations of T cells and in the rates of their maturation may also contribute to the eventual pattern of recovery after irradiation.

The relatively slow recovery of cell mediated immunity after irradiation indicated that total lymphoid irradiation may be a potent modality for the induction of long term immunosuppression. The lack of MLR response during the first 2 yr after radiotherapy, and its slow recovery over the following 2–3 yr indicates that total lymphoid irradiation may prolong the survival of allografts. Indeed, recent preliminary experiments in our laboratory have shown that total lymphoid irradiation by a technique similar to that employed in clinical radiotherapy prolongs the survival of allogeneic skin transplants in mice. The clinical utilization of total lymphoid irradiation as a mode of immunosuppression in patients receiving organ transplants is a provocative idea, but extensive additional studies will be necessary before the merits of such an approach can be fully assessed.

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