Chemotherapeutic agents used in the treatment of childhood malignancies have direct effects on growth plate chondrocyte proliferation

H Robson, E Anderson, O B Eden, O Isaksson and S Shalet
Christie Hospital NHS Trust, Manchester M20 4BX, UK and 1RCEM, University of Goteberg, Goteberg, Sweden
(Requests for offprints should be addressed to H Robson, Department of Tumour Biochemistry, Christie Hospital NHS Trust, Wilmslow Road, Manchester M20 4BX, UK)

Abstract
Short stature is one of the most well recorded long term sequelae for adult survivors of childhood malignancies. It has become increasingly apparent that cytotoxic chemotherapy, as well as craniospinal irradiation, has a major impact on growth, but there are virtually no studies which explore the mechanisms by which these cytotoxic drugs affect growth. We have used an in vitro system to investigate the direct effects of a range of chemotherapeutic agents on the proliferative responses of rat tibial growth plate chondrocytes, both in suspension and monolayer culture.

The glucocorticoids and purine anti-metabolites reduced chondrocyte proliferation both in monolayer and suspension cultures and this resulted from an increase in cell doubling times with a concomittant reduction in the numbers of S phase cells. DNA damaging agents (e.g. actinomycin-D) were also able to reduce chondrocyte proliferation, both in monolayer and suspension culture. This, however, was the result of a cell cycle arrest and subsequent cell death. In our studies, methotrexate had no significant effect on the proliferative responses of the chondrocytes either in monolayer or suspension culture.

These results indicate direct effects of a range of chemotherapeutic agents on the proliferative responses of growth plate chondrocytes. Both cytostatic and cytotoxic effects were observed although the impact of either the potential loss of cells from the proliferative pool during chondrocyte differentiation, or the reduction in the rate of chondrocyte turnover on long bone growth remains to be elucidated.

Introduction
Recent reports suggest that the chemotherapy used in the treatment of childhood malignancies has an effect on growth that is independent of the hypothalamic–pituitary axis, and may reduce the final height of surviving children. Growth retardation following treatment has been demonstrated in several studies (Olshan et al. 1992, Ogilvy-Stuart & Shalet 1995) and there is radiological evidence that the epiphyseal growth plate is damaged in children with acute lymphoblastic leukaemia (ALL) who have received sustained and intensive chemotherapy (Wollner et al. 1980). This is further supported by a large collaborative study between the Manchester, Nottingham and Sheffield paediatric oncology centres (Davies et al. 1994) in which the effects of combination chemotherapy and cranial irradiation on final height and body proportions were examined in a cohort of 142 children treated for ALL. Of the children in the study for whom sitting height measurements were available, 81% had relatively shorter backs than legs and it was suggested that this disproportion might be due to effects of the chemotherapy on the large numbers of epiphyses that are found in the spine. Despite the prevailing clinical evidence it is surprising that there have been few investigations examining local effects of cytotoxic chemotherapy on growth, particularly in terms of long bone growth. The most detailed in vitro experimental studies were performed by Morris (1981), who examined the effects of seven different cytotoxic drugs on insulin-like growth factor-I (IGF-I)-stimulated [35S]sulfate and [3H]thymidine uptake in a porcine costal cartilage bioassay. These studies indicated that cytotoxic chemotherapy may have a direct effect on the response of chondrocytes to changes in the growth hormone (GH)/IGF-I axis. More recently, the glucocorticoid, dexamethasone, was shown to slow proximal tibial growth rate when infused for 4 weeks in 6-week-old rabbits compared with the contralateral vehicle-treated limb (Baron et al. 1994). Following cessation of the dexamethasone treatment, local catch-up growth was observed in the affected growth plate only, suggesting a mechanism intrinsic to the growth plate. In order to address the issue

0022–0795/98/0157–0225 $08.00/0

Downloaded from Bioscientifica.com at 11/18/2018 03:03:53AM via free access
of the effects of chemotherapy on long bone growth, an
*in vitro* system of rat tibial chondrocytes in monolayer and
suspension culture was used. Rat tibial growth plates
provide a readily available and well characterised source
of chondrocytes which, when grown in suspension culture *in vitro*, parallel the differentiation events observed *in vivo* and
are thus an excellent model of chondrogenesis. We have
found that a range of chemotherapeutic agents commonly
used in the treatment of ALL have direct effects on
chondrocyte proliferation *in vitro*.

**Materials and Methods**

**Isolation and culture of chondrocytes**

Chondrocytes were isolated from the tibial epiphyseal
growth plates of 21-day-old male Sprague–Dawley rats as
described by Lindahl *et al.* (1987). In brief, epiphyseal
growth plates were dissected from the rat proximal tibiae
with the aid of a binocular microscope. Pooled growth
plates from 4–5 animals were digested in a 25-cm² tissue
culture flask (Falcon, Oxford, Oxon, UK) for 6–7 h at
37 °C with 0.05% clostridium collagenase/0.02% DNase I (w/v; Sigma, Poole, Dorset, UK) in Ham’s F12 medium
(GIBCO Life Technology, Paisley, Strathclyde, UK).
After isolation, the cells were washed three times in
serum-free medium (SFM) and counted using a haemocytometer. Cell viability at the end of the incubation was
generally >95% as determined by the trypan blue dye
exclusion technique. Subsequently, cells were diluted to a
concentration of 5 x 10⁴ cells/ml in F12 medium supple-
mented with 10% newborn calf serum (NCS; GIBCO
Life Technology) and 50 µg/ml ascorbic acid (AA) (Sigma;
F12/NCS/AA), before seeding at 5 x 10⁵ cells to each
75-cm² tissue culture flask (Falcon). Cells were incubated
at 37 °C in air containing 5% CO₂ and the culture medium
changed after 4 days. Cells were cultured for at least 3 days
post confluence, after which they were trypsinised, washed
in culture medium and counted. The second culture
period was performed either in suspension culture stabi-
lised with agarose or in monolayer culture in 8-well
chamber slides, and 12- or 96-well tissue culture plates.

**Chemotherapeutic agents**

The chemotherapeutic agents employed in all experiments
were prednisolone, dexamethasone, cisplatin, carbo-
platin, etoposide, actinomycin-D, 6-mercaptopurine, 6-
thioguanine and methotrexate which were all obtained
from the Christie Hospital Pharmacy. The doses of each
chemotherapeutic agent used ranged around the peak
plasma levels achieved with these agents *in vivo*.

**Sulphorhodamine B (SRB) proliferation assay**

Proliferation was measured in monolayer culture using the
SRB assay (Skehan *et al.* 1990). By means of a direct
assessment of protein content, this agent provides a
colorimetric endpoint as a highly sensitive measure of
drug-induced cytotoxicity.

Chondrocytes were seeded in 96-well tissue culture
plates (Falcon) at a density of 5000 cells/well in F12/
NCS/AA. Cells were incubated for 24 h at 37 °C in air
containing 5% CO₂ before the addition of fresh medium
(F12/NCS) with or without the chemotherapeutic agents
over the range 0.01–10 µg/ml. Cultures were terminated
after 0, 1, 3 and 6 days by fixation in 10% trichloroacetic
acid (Sigma) for 1 h at 4 °C. Plates were then washed five
times in tap water and air dried before the addition of 0.4%
SRB (Sigma) in 0.1% acetic acid (BDH, Poole, Dorset,
UK) for 1 h at room temperature (RT). Following subse-
quently washing of the wells with 0.1% acetic acid to
remove unbound dye, 100 µl 10 mM Tris–base (Sigma)
was added to each well. Absorption was measured on a
microplate reader (Molecular Devices) at 540 nm within
30 min of adding the Tris–base (10 mM).

**Culture of chondrocytes in suspension stabilised with agarose**

Cells were cultured in agarose according to Benya &
Shaffer (1982). In brief, 60 mm non–tissue culture–treated
Petri dishes (Falcon) were pre–coated with 1% standard
low melting point agarose (autoclaved at 112 °C for
45 min.; Bio–Rad, Richmond, CA, USA). Low melting
point agarose was autoclaved as above and mixed with an
equal volume of F12 to give an agarose concentration of
1%. Cells and F12 were then mixed to give a final agarose
concentration of 0.5% containing 10 000 cells/ml. Three
millilitres of this gel solution were added to each petri dish
(30 000 cells/dish) and the gel was allowed to solidify at
4 °C for 15 min before the addition, on top of the gel, of
Dulbecco’s modified Eagle’s medium (DMEM; GIBCO
Life Technology) mixed with an equal volume of
F12+20% foetal bovine serum (FBS; Biowhittaker,
Wokingham, Berks, UK) with or without addition of the
chemotherapeutic agents over the range 0.01–10 µg/ml.
Thereafter, the cultures were screened for adherent cell
clusters of more than three cells. No such clusters were
seen at the start of culture in any experiments presented
in this study. The suspension cultures were maintained
for 14 days at 37 °C in air containing 5% CO₂ with a
medium change after 7 days to DMEM/F12 mix+10% FBS alone.

**Clonal assay**

Suspension cultures were terminated by fixation in 4% paraformaldehyde (Sigma) in phosphate–buffered saline
(PBS) and stained with alcian blue (0.5% in 0.04 M
hydrochloric acid; Sigma) to identify colonies producing
glycosaminoglycans. Colonies from triplicate dishes were
optically counted and a colony was defined as a cluster of
cells with matrix stained by alcian blue and a diameter >50 µm. Colony numbers and any marked variations in colony size were recorded.

**Cell counts and flow cytometry**

Chondrocytes were seeded in 12-well plates (Falcon) at a density of 50,000 cells/well in F12/NCS/AA and incubated for 24 h before the addition of fresh medium (F12/NCS) with or without chemotherapeutic agents at single submaximally effective doses, as indicated in the figures. Cells were then cultured for up to 7 days at 37 °C in air containing 5% CO₂. At varying time points during this incubation, cells from duplicate wells were trypsinised and counted using a haemocytometer. The remaining cells were then washed and resuspended in a small volume of PBS containing 0·1% BSA (Sigma), 0·1% Triton X-100 (BDH) and 50 µg/ml propidium iodide (PI; Sigma). Cell cycle analysis was performed within 1 h of PI addition using a minimum of 1 × 10⁶ cells and a Becton Dickinson Facscan.

**Bromodeoxyuridine (BrdU) immunohistochemistry**

Chondrocytes were seeded to 8-well Lab Tek tissue culture chamber slides (Nalge Nunc International, Naperville, IL, USA) at 10,000 cells/well in F12/NCS/AA and incubated for 24 h before the addition of fresh medium (F12/NCS) with or without chemotherapeutic agents at single submaximally effective doses as indicated in Table 1. Cells were cultured for 4 days at 37 °C in air containing 5% CO₂, after which time the medium was removed and the cells washed. Fresh medium with 100 µmol BrdU (Sigma) was then added to each well and the cells continuously labelled during an overnight incubation. Wells without BrdU acted as controls. Cultures were subsequently terminated by fixation in 4% paraformaldehyde in PBS for 10 min at RT.

Following a PBS wash, nuclei were exposed by a 30-min incubation at RT with 1 M HCl (BDH) followed by a further 30-min incubation at RT with 0·1 M Na₂B₄O₇ (Sigma). Incubation with a mouse anti-BrdU antibody (Beckton Dickinson, Bedford, MA, USA), 1:100 in PBS, was performed at RT for 1 h followed by three washes in PBS. Bound antibody was detected by the addition of a biotinylated rat anti-mouse antibody (Vector, Peterborough, UK) diluted 1:100 in PBS for 1 h at RT, followed by exposure to the preformed avidin–biotin complex (Vector) for 30 min at RT. Sites of peroxidase activity were visualised with diaminobenzidine tetrahydrochloride plus 0·2% (v/v) hydrogen peroxide (Sigma). Finally, the cells were counterstained with 5% haematoxylin, dehydrated, cleared in histoclear and mounted in DPX mountant. Labelled cells from five separate random fields were counted under the light microscope.

**Statistical analysis**

Mean values were compared by analysis of variance. Comparisons between two means were made using the unpaired Student’s t-test. Differences were considered to be significant when P≤0·05.

**Results**

**Morphology of monolayer cultured chondrocytes**

Following plating of 5 × 10⁵ cells to 75 cm² flasks, a change in cell morphology was observed with time. Cells changed from being initially flattened and mesenchymal-like to appearing characteristically polygonal or round. The plating of rat growth plate chondrocytes at a low density allowed us to select for a population of cells with a high proliferative capacity, thus optimising the measurements made in our subsequent studies. Certainly, an inverse relationship has been shown between cell proliferation and the expression of differentiation markers, such that when the cells are directly plated at confluence (a condition where cell multiplication is impaired) differentiation of chondrocytes and hence maturation readily occurs (Cancedda et al. 1992). Post-confluent chondrocytes tended to be located in dense clusters and extracellular matrix (EM) production was apparent, as visualised by alcian blue staining. Matrix proteoglycan synthesis is also indicative of type II collagen production in these cells, a further characteristic of the chondrogenic phenotype. Dedifferentiated cells started to detach from the culture dish a few days after becoming confluent.

**Proliferation in monolayer culture**

Proliferation was measured at 0, 1, 3 and 6 days following the treatment of rat tibial chondrocytes with the chemotherapeutic agents in monolayer culture. In all treatment arms, cell numbers 24 h after the addition of the drugs were not significantly different from day 0 values. Whilst significant effects on the numbers of cells (P<0·05) were observed in the presence of these agents after both 3 and 6 days of culture, in general these effects were greater at day 3 when compared with the untreated control. The effects of these agents on cell numbers at day 3 are shown in Fig. 1a,b,c. 6-Mercaptopurine and 6-thioguanine significantly (P<0·05; n=5) reduced cell numbers above a threshold concentration of 0·1 µg/ml for both agents although little dose-dependency was observed with either agent between 0·1 and 10 µg/ml (the maximum dose used in these studies). At 10 µg/ml, 6-mercaptopurine and 6-thioguanine significantly reduced cell numbers by 18·31 ± 2·01% and 13·68 ± 4·33% respectively (P<0·05; n=5; Fig. 1a). In contrast, methotrexate had no significant effect on cell number, compared with the control, between 0·01 and 50 µg/ml (n=5).
Both prednisolone and dexamethasone significantly ($P<0.005; n=5$) reduced cell numbers only above a threshold dose of 0.01 µg/ml after which there was no further dose-dependency (Fig. 1b). The reduction in cell numbers observed at 0.01 µg/ml was 1.5 times greater for dexamethasone than for prednisolone.

Figure 1 Dose-response curves of rat proximal tibia growth plate chondrocytes treated with (a) 6-mercaptopurine (●) and 6-thioguanine (■), (b) prednisolone (●) or dexamethasone (■) and (c) carboplatin (■), cisplatin (▲), etoposide (×) or actinomycin-D (●), 24 h after plating 5000 cells/well in a 96-well plate. Chemotherapeutic agents were present continuously during the 3-day incubation. Cells were fixed and stained as described in Materials and Methods. Values are expressed as a percentage of medium alone-treated controls and are the means ± S.D. from five determinations in a single representative experiment.
At the maximum dose employed (10 µg/ml), the DNA damaging agents significantly reduced chondrocyte cell numbers ($P<0.05; n=5$) with an order of potency: actinomycin-D > cisplatin > etoposide > carboplatin (Fig. 1c). For both carboplatin and etoposide the reduction in cell numbers was dose-dependent above a threshold concentration of 0.1 µg/ml, whilst cisplatin dose-dependency occurred above 0.01 µg/ml. In the presence of actinomycin-D, however, cell numbers were significantly reduced at a concentration of 0.01 µg/ml ($P<0.001; n=5$) but remained unchanged at higher concentrations of this drug. At this concentration cell numbers were below that of the day 0 values, indicative of cell death.

The reduction in cell numbers caused by these agents were not significantly different whether they were present in the culture medium for 1 h or continuously throughout the experiment (results not shown).

**Colony formation in suspension culture**

Rat tibial epiphyseal chondrocytes from 21-day-old rats formed small colonies after a culture period of 7 days. After 14 days of culture, the colonies were easily detected under the light microscope. Colonies consisted of varying numbers of cells embedded in a matrix containing proteoglycans, as identified by alcian blue staining (Fig. 2). The cloning efficiency (CE) described by the formula

$$CE = \frac{\text{No. of colonies counted}}{\text{Total no. of cells plated}} \times 100$$

was 3.86 ± 0.003% in control cultures ($n=9$).

Prednisolone and dexamethasone significantly inhibited colony formation ($P<0.005; n=9$) once a threshold dose was reached (Fig. 3b). Consistent with our observations in monolayer culture, a difference in potency between these two agents was noted, such that the threshold dose for dexamethasone was 10 times lower than for prednisolone (0.1 µg/ml and 1 µg/ml respectively). At inhibitory concentrations of these glucocorticoids, although no colony formation was observed, single cells remained in suspension culture that appeared characteristic of a ‘resting’ or ‘stem cell’ population. The cells, often found in pairs, were small in size and showed no EM production.

6-Mercaptopurine and 6-thioguanine significantly ($P<0.005; n=6$) reduced colony formation in suspension culture (Fig. 3a). For example, cloning efficiency was reduced in the presence of 10 µg/ml 6-mercaptopurine and 10 µg/ml 6-thioguanine by 59.5 ± 4.1% and 34.9 ± 9.63% of the controls respectively.

Etoposide, cisplatin, carboplatin and actinomycin-D were all extremely cytotoxic resulting in a total absence of colony formation and the loss of single cells from agarose cultures at concentrations ≥ 1 µg/ml in each instance.
However, methotrexate had no significant effect on the cloning efficiency compared with controls. The size distribution of colonies was not significantly affected by the addition of any of the drugs over the range of concentrations used.

**Cell cycle kinetics**

For analysis of the immediate cytokinetic effects of the chemotherapeutic agents, chondrocyte doubling times, DNA content and BrdU incorporation were determined. The doubling time of exponentially growing untreated chondrocytes in monolayer culture was 39.8 ± 4.3 h (Table 1) and a typical DNA histogram is shown in Fig. 4a.

The glucocorticoids, prednisolone (5 µg/ml) and dexamethasone (5 µg/ml) produced a significant (P<0.005; n=5) prolongation of chondrocyte doubling times in monolayer culture to >4 days (Table 1). This result was paralleled by a significant (P<0.005; n=5) reduction in the numbers of BrdU-labelled cells (Table 1).

The DNA damaging agents cisplatin (1 µg/ml), carboplatin (10 µg/ml) and etoposide (1 µg/ml) all inhibited cell cycle progression. In the presence of carboplatin and etoposide this was characterised by an early G2/M arrest at 24 h, with an associated decrease in the numbers of G1 cells (Fig. 4b,d; Table 2). This effect was maintained, and accompanied at 7 days, by the loss of cells as indicated by the sub-G1 peak. Cisplatin, meanwhile, produced an accumulation of cells in S phase at 24 h, followed by a G2/M arrest at 48 h (Fig. 4c; Table 2). Again, at 7 days cell loss was apparent. Actinomycin-D (0.1 µg/ml) was highly cytotoxic when present in the chondrocyte cultures such that a >95% cell loss occurred. In keeping with its lack of effect on proliferation, methotrexate (5 µg/ml) had no significant effect on cell doubling times (Table 1), numbers of BrdU-labelled cells (n=5; Table 1) or cell cycle kinetics (Table 2).

Both 6-mercaptopurine (10 µg/ml) and 6-thioguanine (10 µg/ml) caused a small but significant (P<0.05; n=5) increase in the mean cell doubling times in monolayer culture from 39.8 ± 4.3 to 46.2 ± 3.2 and 41.9 ± 2.6 h respectively (Table 1), although no changes in cell cycle distribution were observed (Table 2). A significant reduction (P<0.05; n=5) in the numbers of BrdU-labelled cells was observed in the presence of both agents (Table 1).

**Discussion**

Growth plate activity determines the length of the vertebral column and the length of the long bones. During the process of longitudinal bone growth, cells from the germinal zone bordering the bony epiphysis differentiate and start clonal expansion within the proliferative zone. Subsequently, these cells stop dividing, mature and become a part of the hypertrophic zone. Finally, in the zone of calcification the cells degenerate and are incorporated into the metaphyseal bone (Hunziker 1994, Price et al. 1994). This phenotypic flexibility of the chondrocytes in vivo can be mimicked in vitro by cells growing in a suspension culture stabilised with agarose. In the present study chondrocytes were grown in both monolayer and suspension culture. Whilst results from the studies in monolayer cultures provide important information concerning the proliferative capacity of the chondrocyte population as a whole, this is only one aspect of the regulation of long bone growth. For this reason we also studied these cells in a suspension culture assay. This not
only allows the cells to be studied in isolation by measuring their ability to form colonies but it also provides an established in vitro model of chondrogenesis (Lindahl et al. 1987) such that morphological differences as the cells progress towards hypertrophy can be analysed with time. As a result of the chondrocytic isolation from whole growth plates of the proximal tibiae of normal rats, cells grown in suspension culture were heterogeneous in terms of their differentiation and maturation. This results in the formation of either small or large size colonies depending on whether the cells are derived from the proliferative or stem progenitor cells, respectively, within the growth plate (Lindahl et al. 1987). We found that the distribution of small and large size colonies was unaffected by any of the agents used and thus it is possible that they affected chondrocytes at all stages of maturation.

Both dexamethasone and prednisolone, although effective drugs in the treatment of ALL, significantly suppress growth in children (Van Metre & Pinkerton 1959, Falliers et al. 1963). Indeed, in our study dexamethasone and prednisolone, above a threshold concentration, significantly reduced the proliferation and cloning efficiency of chondrocyte cells. BrdU incorporation into these cells suggested that either an interruption or slowing of DNA replication had occurred with these agents or, alternatively, that a significant proportion of the cells were no longer cycling. It is unlikely that the latter is the case, however, since analysis of the DNA histograms following a 48-h incubation of cells with either prednisolone or dexamethasone indicated that the majority of the cells were cycling and undergoing DNA synthesis, albeit rather slowly (Table 2). There is some evidence to suggest that dexamethasone may be more effective than prednisolone in the treatment of ALL (Kaspers et al. 1996) and whilst this is important for the treatment of childhood malignancies we should be aware that this increased potency may also impact upon growth plate chondrocytes. Certainly, in suspension culture dexamethasone was ten times more potent than prednisolone in terms of reducing chondrocyte cloning efficiency, which is consistent with a 7-fold increase in potency observed with this agent in vivo (Kaspers et al. 1996). However, despite the inability of dexamethasone- or prednisolone–treated cells to form colonies in suspension culture, single cells, having characteristics of those cells found in the stem or reserve cell layer of the growth plate, clearly remained in culture. During chondrocyte differentiation the resting or stem cells have an extremely long generation time and act merely as a pool from which daughter cells are fed into the adjacent proliferating cell layer for subsequent clonal expansion. As we have already mentioned, however, our chondrocyte population was heterogeneous in terms of its origin from within the growth plate, and thus a proportion of the cells must be derived from the proliferative layer. Nevertheless, it is possible that these agents do act by suppressing stem cell proliferation, preventing their differentiation to IGF-I-responsive cells and thereby delaying senescence. In a study examining the differentiation of 3T3-F442A fibroblasts, it was reported that continued treatment with dexamethasone inhibits their terminal differentiation to the adipocyte-like phenotype (Piauault & Lasnier 1987). Certainly, in the rabbit proximal tibial growth plate in vivo, dexamethasone was shown to slow the growth rate compared with a contralateral vehicle-treated control. This was followed by local catch-up growth that was restricted to the affected growth plate (Baron et al. 1994). Under physiological conditions in the rat, each stem cell undergoes ≈40–50 cell divisions. Each cell division gives rise to approximately 30 hypertrophic chondrocytes and each hypertrophic chondrocyte per column contributes approximately 30 μm linear growth (Kember 1971). The slower division of stem cells would, therefore, delay growth. However, if the subsequent proliferation of non-stem daughter cells was also suppressed, then the glucocorticoids may also reduce the numbers of hypertrophic chondrocytes arising from each stem cell division. A decrease in clone size per stem cell division may lead to irreversible loss of linear growth.

Table 1 Cell doubling time and S phase fraction in rat proximal tibial growth plate chondrocytes following incubation for three days with or without chemotherapeutic agents. Doubling times were determined in a single experiment and are the mean ± S.E.M. (n= 5). S phase fractions were measured using BrdU immunohistochemistry. Values are the mean ± S.D. from a single representative experiment (n= 5).

<table>
<thead>
<tr>
<th>Agent</th>
<th>Doubling times (h)</th>
<th>BrdU-labelled cells (% control)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>39·8 ± 4·3</td>
<td>—</td>
</tr>
<tr>
<td>Prednisolone (5 μg/ml)</td>
<td>96·2 ± 5·2**</td>
<td>30·99 ± 4·56**</td>
</tr>
<tr>
<td>Dexamethasone (5 μg/ml)</td>
<td>98·7 ± 4·1**</td>
<td>24·56 ± 3·89**</td>
</tr>
<tr>
<td>6-Mercaptopurine (10 μg/ml)</td>
<td>46·2 ± 3·2*</td>
<td>47·37 ± 4·04**</td>
</tr>
<tr>
<td>6-Thioguanine (10 μg/ml)</td>
<td>41·9 ± 2·6*</td>
<td>68·13 ± 6·17*</td>
</tr>
<tr>
<td>Methotrexate (5 μg/ml)</td>
<td>43·7 ± 5·2 ns</td>
<td>81·58 ± 8·42 ns</td>
</tr>
</tbody>
</table>

*P<0·05, **P<0·005, ns not significant, compared with control (Students t-test).
Figure 4 Changes in the cell cycle kinetics of exponentially growing chondrocyte cells at 0, 24, 48 and 168 h following treatment with (a) medium alone, (b) carboplatin (10 μg/ml), (c) cisplatin (1 μg/ml) and (d) etoposide (1 μg/ml). Cells for flow cytometry were prepared as described in Materials and Methods. DNA histograms are ungated and show G1 (M1), S (M2) and G2/M (M3) peaks. Sub-G1 peaks are indicative of cellular apoptosis.
6-Mercaptopurine and 6-thioguanine are designed to disrupt the purine salvage pathway and to interfere with the normal supply of nucleotides for DNA synthesis. Both compounds eventually form the same abnormal 6-thioguanine nucleotides, although the way they are metabolised to produce the cytotoxic chemicals differs (McCormack & Johns 1982). Inhibition of purine de novo synthesis reduces purine deoxyribonucleotide levels and can be demonstrated by the delay of cell progression through S phase and an inhibition of DNA synthesis. Indeed, Bokkerink et al. (1993) demonstrated a G2 arrest in human malignant T lymphoblasts after a 24-h incubation with 6-mercaptopurine. 6-Thioguanine, however, is a cell cycle specific agent, killing cells in G1 and S phases (Le Page 1963). Although in our studies cell doubling times were slightly increased by both agents, it was perhaps surprising that no effects of these agents were observed on cell cycle events, particularly as both also inhibited early cell growth and clonal growth, with a lesser effect on cytotoxicity. Furthermore, the significant reduction in the numbers of BrdU-labelled cells observed in our studies is likely to be due merely to the competition between either agent and BrdU for uptake during purine nucleotide synthesis. What is possible, however, is that the level of toxicity observed with these agents is dependent on length and frequency of exposure, resulting from an accumulated toxicity, and thus the repeated daily exposure of chondrocytes in culture to these agents may produce greater effects than single exposures. In vivo studies have reported that, following daily administration for 5 days, 6-thioguanine is ten times more potent than 6-mercaptopurine (Adamson et al. 1994). This was certainly not the case in our studies, however, where a significantly greater effect of 6-mercaptopurine on cloning efficiency was observed.

Methotrexate is an antiproliferative agent that accumulates intracellularly as polyglutamate derivatives and inhibits DNA synthesis via inhibition of the enzyme dihydrofolate reductase (Van der Veen et al. 1996). In our studies we failed to observe any effects of this agent on the proliferative responses of the chondrocytes. Again this may be due to the absence in our studies of an examination of the cumulative effects of this agent with time. Certainly, long term low dose treatment with methotrexate can cause osteopathy with histologically proven reduction in bone turnover and matrix formation (Preston et al. 1993, Jaskiewicz et al. 1996).

The DNA damaging agents etoposide, actinomycin-D, cisplatin and carboplatin exhibit varying mechanisms of cytotoxicity. Etoposide is a topoisomerase II inhibitor which has been reported to induce an irreversible blockade of cells in the pre-mitotic phase of the cell cycle, leading to the accumulation of cells in the late S or G2 phases (Achterrath et al. 1982). Indeed, a G2 arrest and significant loss of the chondrocytes was observed in our studies, which was also characterised by the loss of cloning efficiency.

Actinomycin-D suppresses RNA synthesis (Perry & Kelly 1970) although it is not known why some cells die after a brief exposure to this agent and others do not, nor why the cytotoxic effects are reversible for some cells and not for others. Certainly, in our studies this agent was extremely cytotoxic and an almost complete loss of chondrocytes was observed in all assays.

Part of the cytotoxic mechanism of cisplatin action involves the formation of intrastrand DNA cross-links between guanosine residues (Sherman et al. 1985), effects that were previously shown to be most pronounced during S phase. In our studies, an early S phase accumulation observed in chondrocyte cells treated with cisplatin was followed by their arrest in G2/M and subsequent cell loss.

Carboplatin was shown by Micetich et al. (1985) to cause similar types of DNA lesions to cisplatin, but carboplatin does this more slowly than cisplatin. Carboplatin was certainly significantly less potent than

### Table 2

<table>
<thead>
<tr>
<th>Agent</th>
<th>G1 (%)</th>
<th>S (%)</th>
<th>G2/M (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>67.79</td>
<td>4.60</td>
<td>13.61</td>
</tr>
<tr>
<td>Prednisolone (5 µg/ml)</td>
<td>77.48</td>
<td>2.20</td>
<td>11.62</td>
</tr>
<tr>
<td>Dexamethasone (5 µg/ml)</td>
<td>77.02</td>
<td>2.08</td>
<td>12.10</td>
</tr>
<tr>
<td>6-Mercaptopurine (10 µg/ml)</td>
<td>69.52</td>
<td>3.80</td>
<td>12.56</td>
</tr>
<tr>
<td>6-Thioguanine (10 µg/ml)</td>
<td>75.17</td>
<td>5.40</td>
<td>11.25</td>
</tr>
<tr>
<td>Cisplatin (1 µg/ml)</td>
<td>30.14</td>
<td>18.37</td>
<td>20.66</td>
</tr>
<tr>
<td>Carboplatin (10 µg/ml)</td>
<td>50.62</td>
<td>6.96</td>
<td>21.65</td>
</tr>
<tr>
<td>Etoposide (1 µg/ml)</td>
<td>44.09</td>
<td>11.79</td>
<td>19.43</td>
</tr>
<tr>
<td>Methotrexate (5 µg/ml)</td>
<td>65.82</td>
<td>2.78</td>
<td>12.31</td>
</tr>
</tbody>
</table>
cisplatin in terms of its cytotoxic effects on chondrocyte cells in monolayer culture, although in suspension culture both agents were able completely to abolish colony formation.

In summary, in our studies the glucocorticoids and to some extent the purine salvage pathway inhibitors exert cytostatic effects on the chondrocytes whilst the DNA damaging agents are cytotoxic. What is clear, however, is the importance of determining the long-term effects of these agents on chondrocyte differentiation and maturation and their subsequent recovery, if any. Of particular interest is the observation that under certain pathological conditions, mechanisms regulating the cellular height of the hypertrophic chondrocyte may be impaired without disturbing proliferative capacity. Furthermore, both GH and IGF-I have important roles in the regulation of longitudinal bone growth such that these peptides stimulate the chondrocytes at different stages of maturation. GH affects the chondro-progenitor, or stem cells and IGF-I affects the proliferative chondrocytes. Direct stimulation by GH sensitises the pre-chondrocytes and young differentiating cells to IGF-I (reviewed by Hunziker 1994). It is thus possible that both peptides could aid the recovery of chondrocytes following their treatment with these agents. However, long-term treatment with glucocorticoids in rheumatic diseases has been linked to reduced bone formation which, in turn, was suggested to be due to a decrease in the sensitivity of the target to IGF-I (Hansson et al. 1996). Furthermore, although we saw no effect with the agent methotrexate in our studies, this does not rule out the possibility of adverse effects following prolonged and/or repeated exposure with this agent or at different stages of chondrocyte maturation.

In conclusion, these results have important implications for the control of longitudinal bone growth in vivo and the consequences of treatment for childhood malignancies. Further studies will be undertaken to determine the mechanism(s) of agent action in these cells as well as their role during the overall regulation of chondrocyte maturation and the possible contribution of treatment schedules to these effects.

Acknowledgements

This work was supported by the Christie Hospital Endowment Fund

References


Jaskiewicz K, Voight H & Blakolmer K 1996 Increased matrix proteins, collagen and transforming growth factor are early markers of hepatotoxicity in patients on long-term methotrexate therapy. Journal of Toxicology and Clinical Toxicology 34 301–305.


Received 11 June 1997
Accepted 24 November 1997