Non-growing follicle density is increased following adriamycin, bleomycin, vinblastine and dacarbazine (ABVD) chemotherapy in the adult human ovary

Citation for published version:

Digital Object Identifier (DOI):
10.1093/humrep/dew260

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Peer reviewed version

Published In:
Human Reproduction

General rights
Copyright for the publications made accessible via the Edinburgh Research Explorer is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy
The University of Edinburgh has made every reasonable effort to ensure that Edinburgh Research Explorer content complies with UK legislation. If you believe that the public display of this file breaches copyright please contact openaccess@ed.ac.uk providing details, and we will remove access to the work immediately and investigate your claim.
Non-growing follicle density is increased following adriamycin, bleomycin, vinblastine and dacarbazine (ABVD) chemotherapy in the adult human ovary

<table>
<thead>
<tr>
<th>Journal:</th>
<th>Human Reproduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manuscript ID</td>
<td>HUMREP-16-0787.R1</td>
</tr>
<tr>
<td>Manuscript Type:</td>
<td>Original Article</td>
</tr>
<tr>
<td>Date Submitted by the Author:</td>
<td>23-Aug-2016</td>
</tr>
</tbody>
</table>
| Complete List of Authors: | McLaughlin, Mary; University of Edinburgh, Centre for Integrative Physiology and Institute of Cell Biology  
                           Kelsey, tom; University of St. Andrews, 3) School of Computer Science  
                           Wallace, Wiliam; Department of Reproductive and Developmental Sciences, Division of Child Life and Health,, University of Edinburgh  
                           Anderson, Richard; University of Edinburgh, MRC Centre for Reproductive Health  
                           Telfer, Evelyn; University of Edinburgh, Centre for Integrative Physiology and Institute of Cell Biology |
| Keywords:    | OVARY, follicle, lymphoma, ABVD, oocyte |
| Subject Section: | Reproductive Biology |
Non-growing follicle density is increased following adriamycin, bleomycin, vinblastine and dacarbazine (ABVD) chemotherapy in the adult human ovary

M. McLaughlin¹,², T.W. Kelsey³, W.H.B. Wallace⁴, R.A. Anderson⁵ E.E. Telfer¹,²*

¹Centre for Integrative Physiology, University of Edinburgh, Edinburgh EH8 9XD, UK
²Institute of Cell Biology, University of Edinburgh, Edinburgh EH9 3BF, UK
³School of Computer Science, University of St. Andrews, St. Andrews KY16 9SX, UK
⁴Department of Haematology/Oncology, Royal Hospital for Sick Children, Edinburgh EH9 1LF, UK.
⁵MRC Centre for Reproductive Health, University of Edinburgh, Edinburgh EH16 4TJ, UK.

Running Title: Chemotherapy and non-growing follicle density

*Correspondence address: Centre for Integrative Physiology, University of Edinburgh, Hugh Robson Building, Edinburgh EH8 9XD, UK.

Email: Evelyn.Telfer@ed.ac.uk
Abstract

Study question: Do the chemotherapeutic regimens of ABVD (adriamycin, bleomycin, vinblastine and dacarbazine), or OEPA-COPDAC (combined vincristine, etoposide, prednisone, doxorubicin (OEPA) and cyclophosphamide, vincristine, prednisone, dacarbazine (COPDAC)) used to treat Hodgkin lymphoma, affect the density, morphology and in vitro developmental potential of human ovarian follicles?

Summary answer: Ovarian tissue from women treated with ABVD contained a higher density of non-growing follicles/mm$^3$ and increased numbers of multi-ovular follicles, but showed reduced in vitro growth compared with patients with lymphoma who had not received chemotherapy, patients treated with OEPA-COPDAC, age-matched healthy women and age-related model-predicted values.

What is known already: Chemotherapy regimens can cause a loss of follicles within the ovary that depends on the drugs given. Early stage Hodgkin lymphoma is commonly treated by ABVD, a non-alkylating regimen which apparently has ovarian sparing qualities, thus it is important to investigate the histological appearance and distribution of follicles within ABVD-treated ovarian tissue.

Study design, size, duration: Thirteen ovarian biopsies were obtained from Hodgkin lymphoma patients (6 adolescents and 7 adults) and one biopsy from a non-Hodgkin lymphoma patient. Two Hodgkin lymphoma patients and the non-Hodgkin lymphoma patient had received no treatment prior to biopsy collection. The remaining 11 Hodgkin lymphoma patients received one of two regimens; ABVD or OEPA-
COPDAC. Tissue was analysed histologically and compared to biopsies from healthy women, and in a sub-group of patients, tissue was cultured for 6 days in vitro.

**Participants/materials, setting, methods:** Ovarian biopsies were obtained from patients undergoing ovarian cryopreservation for fertility preservation, and from healthy women at the time of Caesarian section (‘obstetric tissue’). Follicle number and maturity were evaluated in sections of ovarian cortical tissue, and compared to an age-related model of mean follicle density and to age-matched contemporaneous biopsies. The developmental potential of follicles was investigated after 6 days tissue culture.

**Main results and the role of chance:** A total of 6877 follicles was analysed. ABVD-treated tissue contained a higher density of non-growing follicles/mm$^3$ (230±17) (mean±SEM) than untreated (110±54), OEPA-COPDAC-treated (50±27) and obstetric tissue (20±4) ($P<0.01$), with follicle density 9-21 standard deviations higher than predicted by an age-related model. Bi-ovular and binucleated non-growing follicles occurred frequently in ABVD-treated and in adolescent untreated tissue but were not observed in OEPA-COPDAC-treated or obstetric tissue, although OEPA-COPDAC-treated tissue contained a high proportion of morphologically abnormal oocytes (52% versus 23% in untreated, 22% in ABVD-treated and 25% in obstetric tissue; $P<0.001$). Activation of follicle growth in vitro occurred in all groups, but in ABVD-treated samples there was very limited development to the secondary stage, whilst in untreated samples from lymphoma patients growth was similar to that observed in obstetric tissue (untreated; $P<0.01$ versus ABVD-treated, ns versus obstetric).
Large scale data: N/A

Limitations, reasons for caution: Although a large number of follicles were analysed, these data were derived from a small number of biopsies. The mechanisms underpinning these observations have yet to be determined and it is unclear how they relate to future fertility.

Wider implications of the findings: This study confirms that the number of non-growing follicles is not depleted following ABVD treatment, consistent with clinical data that female fertility is preserved. Our findings demonstrate that immature follicle density can increase as well as decrease following at least one chemotherapy treatment. This is the first report of morphological and follicle developmental similarities between ABVD-treated tissue and the immature human ovary. Further experiments will investigate the basis for the marked increase in follicle density in ABVD-treated tissue.

Study Funding/competing interests: Funded by UK Medical Research Council Grants G0901839 and MR/L00299X/1. The authors have no competing interests.

Keywords: ovary/ follicle/ lymphoma/ ABVD/oocyte/primordial/chemotherapy/regeneration/ modelling
Introduction

The number of follicles in the ovary decreases progressively with age. Treatments such as some chemotherapy agents can accelerate this loss leading to premature ovarian insufficiency (POI) with loss of fertility and estrogen deficiency in female survivors of cancer (Morgan et al., 2012). The likely range of mechanisms of drug-induced ovarian damage has yet to be fully characterised but includes direct damage to growing and non-growing follicles, and loss of growing follicles may lead to the recruitment of dormant follicles to the growing phase which in turn are lost, thus accelerating the depletion of the non-growing pool, i.e. the ovarian reserve (Meirow et al., 2010; Morgan et al., 2012; Kalich-Philosoph et al., 2013).

Since the mid-1970s the standard first line treatment for early stage Hodgkin lymphoma (HL) in many countries has been adriamycin, bleomycin, vinblastine and dacarbazine (ABVD) (Bonadonna and Santoro, 1982; Meirow and Nugent, 2001; Meyer et al., 2012). Early stage HL patients receiving ABVD based treatment where involved field radiotherapy does not include the ovaries have a good reproductive prognosis for both fertility and risk of POI (Hodgson et al., 2007, Swerdlow et al., 2014, ). In contrast advanced stage HL patients treated with a drug regimen containing one or more alkylating agents and involved field radiotherapy have a higher prevalence of POI (Behringer et al., 2005), and should therefore be considered for fertility preservation strategies before commencing treatment (Anderson et al., 2015).

The purpose of this study was to examine microscopically, ovarian tissue from patients with lymphoma exposed to ABVD chemotherapy and compare this with samples exposed to the combined alkylating chemotherapeutic regime (OEPA-
COPDAC)(combined vincristine, etoposide, prednisone, doxorubicin (OEPA) and cyclophosphamide, vincristine, prednisone, dacarbazine (COPDAC), with samples not previously exposed to chemotherapy and with further samples from healthy women to determine whether follicle density, morphology and in vitro developmental potential were affected by these chemotherapeutic interventions. Comparing follicle densities across treatments requires identification of changes to non growing follicle(NGF) cortical densities in comparison with those predicted by age related models (Kelsey & Wallace., 2012; Kelsey et al., 2013). In this study we used a recently reported validated age-related model of mean follicle density(MFD) in the ovarian cortex (McLaughlin et al., 2015), to compare observations of MFD in tissue obtained after different chemotherapy regimens.

Materials and Methods

Patient Selection

Diagnosis, patient age, chemotherapeutic regimen, anti-Müllerian hormone (AMH) concentrations and time between completion of treatment and biopsy collection are detailed in Table 1.

Ovarian Cortical Tissue

Ovarian biopsies were obtained laparoscopically from 6 adolescents and 7 adults diagnosed with Hodgkin lymphoma and 1 adult diagnosed with non-Hodgkin lymphoma. All patients were undergoing removal of ovarian cortex for fertility cryopreservation either prior to chemotherapy or following relapse of previously treated illness. Protocols for tissue donation for research had Ethical Committee approval from South East Scotland Research Ethics Committee (ref 06/S1103/26) and all patients gave informed consent in writing. The mean patient age was...
20.2±1.5 years (mean ±SEM) with a range of 12.0 – 30.0 years. For analyses patients were divided into 3 groups: those treated with ABVD (aged 16 – 29 years, n = 8), those treated with OEPA-COPDAC (aged 14 – 16 years, n = 3) and untreated patients or controls (aged 12 – 30 years, n = 3). Data were compared with results obtained from contemporaneous ovarian biopsies obtained from adult women undergoing elective Caesarean section (age range 23 – 39 years, n = 12) prepared and processed in an identical manner, also obtained with written informed consent and Ethical committee approval (ref 10/S1101/24).

Tissue preparation and processing

Fresh ovarian biopsies (ranging in size from 8x5mm and 6x4mm all with variable thickness) were transported to the laboratory in holding medium (Leibovitz medium, Gibco; Life Technologies, Paisley, Renfrewshire, UK supplemented with 2mM sodium pyruvate, 2mM L-glutamine, 3mg/ml human serum albumin, 75mg/ml penicillin G and 50mg/ml streptomycin; all chemicals from Sigma-Aldrich, Poole, UK). Tissue was transferred into fresh pre-warmed (37°C) holding medium and examined under a dissecting light microscope. A scalpel and fine forceps were used to remove any damaged or haemorrhagic areas as well as any tissue adhering to the underside of the biopsies to leave only intact cortex in place. Using a scalpel the tissue was divided into fragments of approximately 4 x 2 x 0.5 mm; the number of fragments varied between biopsies. Fragments were fixed in 10% neutral buffered formalin (NBF) for 48h then processed and prepared for staining and microscopic evaluation as previously described (McLaughlin et al., 2014).

Thawing of cryopreserved tissue
Two of the biopsies were cryopreserved by slow freezing (Gosden et al., 1994) and were donated for research at the patients’ request. Tissue was thawed as described previously (Anderson et al., 2014), inspected, divided into fragments, fixed and processed for staining and analysis as described above.

Assessment of mean follicle density in ovarian biopsies

Each histological section of every tissue fragment was examined under light microscopy. Follicles were categorised according to their stage of development as previously described (Telfer et al., 2008; McLaughlin et al., 2014). To avoid over-counting, only follicles containing the nucleolus were assessed. The volume of tissue analysed per patient was calculated as described previously (Lass et al., 1997; Anderson et al., 2014). Briefly, tissue volume was calculated as the sum of the area in mm$^2$ of all tissue sections analyzed per patient, multiplied by 0.006 mm (the thickness of the sections) to give a value in mm$^3$. The area of each section was measured and mean follicle density was determined by dividing the total number of follicles per patient by the volume of tissue analyzed in mm$^3$ (Anderson et al., 2014).

Evaluation of histology

Evaluation of the tissue sections was performed blinded to the treatment groups. Follicles in freshly fixed and cultured tissue pieces were categorised by developmental stage based on morphology as previously described (McLaughlin et al., 2014). Follicle morphological normality was determined by an assessment of the appearance of the oocyte and surrounding cells using the cross-section containing the nucleolus as described previously (McLaughlin and Telfer, 2010, McLaughlin et al., 2014). The presence of bi-ovular and binucleate follicles was also noted.
The spatial relationship between follicles was also assessed and classified as (1) single i.e. no follicles within 15 µm of the follicle being evaluated, (2) in close proximity i.e. at least one other follicle occurring within 15µm of the follicle being evaluated or (3) direct contact i.e. where 2 or more follicles appeared to share the same basal lamina or the basal laminae of 2 or more follicles abutted. Follicles were classified as occurring in clusters if 5 or more follicles were found in direct contact or close proximity. The presence of naked oocytes with few or no surrounding cells was also noted.

**Fragment culture**

Prior to fixation a number of tissue fragments were selected at random from a sub-section of the ABVD-treated patients (n = 4; age range 23 - 29 years), 1 OEPA-COPDAC-treated patient (16 years), 2 untreated controls (15 years and 30 years) and from obstetric patients (n = 10; age range 23 – 36 years). Between 2 and 6 fragments were obtained for each patient, prepared for culture and incubated for 6 days then processed for histological evaluation as previously described (McLaughlin et al., 2014).

**Immunohistochemistry**

A number of ABVD-treated, OEPA-COPDAC-treated and control tissue fragments fixed in NBF and embedded in paraffin as described previously (McLaughlin et al., 2014) were selected at random and cut in 6µm sections and mounted on charged slides to investigate the expression of the germline marker protein DEAD box polypeptide 4 (DDX4). Antigen retrieval was performed using 0.01M sodium citrate and endogenous peroxidase activity quenched by 3% hydrogen peroxide in
methanol. Tissue sections were incubated in anti-DDX4/MVH ab13840 polyclonal primary antibody (Abcam, Cambridge, UK) overnight at 4°C. Negative controls were established by replacing the primary antibody with goat serum. On completion of incubation, sections were washed and probed with anti-rabbit secondary antibody labelled with horseradish peroxidase for 30 mins (ABC-Elite Rabbit IgG, Vectastain Elite Kit, PK-6101, Vector Laboratories Ltd, Peterborough, UK). DDX4 was detected using 3, 3’-diaminobenzidine (DAB) peroxidase substrate kit (Vector Laboratories Ltd, Peterborough, UK). Structures were positively identified as germ cells when brown staining was observed within a cell.

**Statistical analysis**

Observed mean follicle densities were compared to predicted mean follicle densities using an age-related model of mean follicle density in the cortex of the human ovary (McLaughlin *et al*., 2015). Chi-Square Goodness-of-Fit analysis was used to test the null hypotheses that the observations matched predicted MFD. Pearson's product-moment correlation coefficients were also calculated to compare data to the line of identity where predictions exactly match observations. Due to the need for high confidence in the significance of any observed differences between predicted and observed densities, statistical significance was set at the 99% level throughout. Bland-Altman analysis was used to estimate the number of standard deviations away from agreement between observations and predictions using the limits of agreement reported in McLaughlin *et al.* (2015).

**Results**

**Follicle density**
The number of follicles and their developmental stage were determined by examining fresh and post-thawed fixed ovarian tissue from 14 previously treated and untreated lymphoma patients and an age-matched group of 12 obstetric patients; a total of 6877 follicles were examined. The total number of follicles counted in each group and the volume of tissue analysed are shown in Table 2. Ages and MFDs for the three groups of lymphoma patients are shown in Fig. 1A, together with age-related predictions taken from McLaughlin et al., (2015). For the three patients who received no chemotherapy we have insufficient evidence to reject the null hypothesis that the observed values for MFD are a perfect fit with predicted values taken from the age-related model derived from data from other subjects receiving no chemotherapy: Chi-square p-value = 0.07; Pearson's product-moment correlation coefficient = 0.999 (p < 0.01, Fig. 1B) with the observations within 1.25 standard deviations of agreement between observed and predicted values (Fig. 1C). The three patients who received OEPA-COPDAC chemotherapy had significantly lower observed MFD than predicted: Chi-square p-value < 0.01; Pearson's product-moment correlation coefficient = -0.399 (p = 0.74, Fig. 1B) with the observations between 0 and 11 standard deviations lower than the predictions (Fig. 1C). However, the eight patients who had received ABVD chemotherapy had higher numbers of non-growing follicles (160-303/mm³) compared with samples from healthy women (8-46/mm³) (Table 2). The ABVD group had significantly higher observed than predicted MFD: Chi-square p-value < 0.001; Pearson's product-moment correlation coefficient = 1.57 (p = 0.71, Fig. 1B) with observations between 9 and 21 standard deviations higher than the predictions (Fig. 1C).
Time elapsed between completion of chemotherapy regimen and biopsy ranged from 1 to 36 months, with six of the eight ABVD-treated patients having tissue collected within 6 weeks and all OEPA-COPDAC patients undergoing biopsy within 9 months of treatment. No correlation was found between the time interval and the MDF observed in tissue treated with either regimen: the marked increase in MFD in ABVD-treated tissues was observed in biopsies taken within 4 weeks of chemotherapy completion and was also present in samples taken up to 36 months after treatment, although the small sample size at the later treatment times does not allow for time after treatment to be robustly tested. The OEPA-COPDAC tissue from two out of three patients showed follicle numbers below that predicted at 6-9 months post treatment. Biopsy tissue was only available from each patient at one time point therefore it was not possible to investigate by histological means whether deterioration or recovery of NGF density occurred over time.

Follicle categorisation

The majority of all follicles observed in fixed tissue were non-growing irrespective of illness, treatment or age (Fig. 2A). However ABVD-treated tissue contained a significantly smaller percentage of growing follicles (3.0%) compared to untreated, OEPA-COPDAC-treated and obstetric patients (15.6%, 21.4% and 18.0% respectively; p< 0.001) (Fig. 2A).

Analysis of oocyte appearance showed that in biopsies collected from untreated, ABVD-treated and obstetric patients, morphological normality was high with >74% of oocytes appearing normal. In contrast less than half of the oocytes in follicles observed in OEPA-COPDAC-treated tissue met the criteria for normality (41.9% in...
OEPA-COPDAC compared to 76.8% in untreated; 78.4% in ABVD-treated and 74.2% in obstetric samples; \( p < 0.001 \) (Fig. 2C and D).

**Follicle development in cultured tissue**

To investigate the *in vitro* developmental potential of chemotherapy-exposed follicles, tissue fragments from a subset of patients representing each group were cultured for 6 days. It was not possible to culture fragments from every patient due to the limited amount available. A total of 89, 614 and 274 follicles were analysed in cultured tissue obtained from untreated \( (n = 2) \), ABVD-treated \( (n = 4) \) and obstetric patients \( (n = 10) \) respectively. Analysis of cultured tissue fragments from two patients treated with OEPA-COPDAC has been omitted due to extreme follicle degeneration in both patients. Initiation of follicle growth was observed in all of the 3 remaining groups. Post-culture the proportion of growing follicles was 19.9% in ABVD-treated tissue, 41.6% in untreated tissue and 46.3% in obstetric samples \( (all \ P < 0.001 \) versus uncultured) (Fig. 3A). Development to the secondary stage occurred in both untreated and obstetric groups with 18% and 18.2% of follicles observed reaching this stage respectively whereas very few follicles progressed in the ABVD-treated tissue, comprising only 1.2% of follicles at the secondary stage after culture (Fig 3B and C).

**Immunohistochemical localization of DDX4**

Due to the high density of non-growing follicles observed in ABVD-treated tissue and the presence of clusters, bi-ovular and binucleate follicles, immunohistochemistry was performed to examine whether the germline marker DDX4 could be localized in these structures. Uncultured tissues sections from 9 patients representing all groups
were studied; the number of sections per patient was variable due to tissue availability, and the number of follicles per section was also highly variable. Discrete positive DDX4 staining was observed in oocytes of follicles at all stages of development in all groups. DDX4 was also localised to the bi-ovular and binucleate oocytes and clusters of naked oocytes with adjacent or shared oolemmae observed in ABVD-treated tissue. No positive staining was observed in any tissue sections where the primary antibody had been omitted (Fig. 3D).

**Spatial distribution of follicles**

In all groups individual follicles and groups of follicles were distributed unevenly throughout the cortex however the pattern of distribution varied between groups with the majority of follicles occurring discretely (single follicles ≥ 15µm apart) in obstetric tissue (Fig. 4A and B). ABVD-treated and untreated adolescent tissues appeared markedly different from the others examined, with significantly fewer discrete follicles seen and clusters of closely packed follicles (5 or more NGF ≤ 15µm apart) observed in these groups (p < 0.05; ABVD-treated and untreated versus OEPACOPDAC-treated and obstetric patients (Fig. 4A and C). Bi-ovular and binucleate follicles were observed in ABVD-treated tissues and also in the 12 year old untreated patient's tissue comprising between 8-18% of the NGF population. These structures were not observed in the other tissues examined. Follicle clusters often contained naked or partially naked oocytes, which otherwise appeared morphologically normal (Fig 4C).

**Discussion**
Ovarian dysfunction and reduced fertility potential can be a consequence of cytotoxic therapy particularly where alkylating agents have been used, with resultant loss of the ovarian reserve (Meirow et al., 2010). In contrast women diagnosed with lymphoma and treated with the gonad-sparing regimen ABVD have a low risk of significant impairment of fertility (Hodgson et al., 2007) or of POI (Swerdlow et al., 2014) and no reduction in follicle numbers have been observed (Seshadri et al., 2006). The impact of chemotherapy on the ovarian reserve is evaluated indirectly by clinical parameters including amenorrhea, AMH and FSH levels (Meirow, 2000; Oktay et al., 2006; Anderson and Cameron, 2011). Post-treatment AMH levels in lymphoma patients clearly show the differential impact of ABVD and alkylating agent based regimens (Decanter et al., 2010) and AMH levels may also be reduced at the time of diagnosis (Lawrenz et al., 2012). Although early studies showed that chemotherapy reduced the number of antral follicles in the ovary in girls treated for leukaemia (Himelstein-Braw et al., 1978), this is the most detailed quantitative analysis of the direct effect of chemotherapy treatment on density of the ovarian reserve in lymphoma patients and the impact of the different chemotherapy regimens on morphology and in vitro developmental potential of follicles. In this study we have identified and quantified differences in the non-growing follicle population of treated and untreated lymphoma patients. The observed MFD of untreated lymphoma patients were close to the densities predicted by an age-related model indicating that the disease itself is not implicated in the variation of the ovarian reserve observed in the chemotherapy-treated groups.

Treatment regimens containing alkylating agents such as cyclophosphamide are known to lead to POI via a direct or indirect reduction in the NGF population (Oktem and Oktay, 2007; Meirow, 2000; Meirow et al., 2010). Our finding that patients treated
with the OEPA-COPDAC regimen had lower than predicted MFDs confirms and
quantifies this, although the MFD in this small group varied from very low to close to
average for age. Further analysis of the degree of loss is not possible without
knowing pre-treatment values. In this study patients treated with OEPA-COPDAC
were all teenagers (14, 15 and 16 years) at the time of tissue collection, which was
6-9 months after completion of chemotherapy. Of the 3 patients included in this study
treated with OEPA-COPDAC one was diagnosed with reduced ovarian reserve
based on having regular menstrual cycles but undetectable AMH levels one year
after completion of treatment and another was diagnosed with POI 6 years post
chemotherapy.

Surprisingly we found a striking and statistically highly significant increase in follicle
number and MFD after ABVD chemotherapy. All eight ABVD patients had higher
follicle counts (Table 2) and a markedly higher follicle density than predicted (Fig.
2C). Despite the well reported variation of follicle density between and within human
cortical biopsies follicles (Kohl et al., 2000; Qu et al., 2000; Poirot et al., 2002;
Schmidt et al., 2003; McLaughlin et al., 2015), all ABVD-treated samples consistently
showed an increase in the NGF population whereas this was not seen for any of the
other groups or individual biopsies. We initially considered that this increase might be
attributed to a reduction in ovarian volume during treatment as all treatments would
result in an initial reduction in ovarian volume because of the loss of large
follicles. However, MFD is based on volume of ovarian cortex, not whole ovary and
there is no evidence to support a differential effect on ovarian cortex volume by any
treatment. Additionally, these samples were collected 4 weeks to 36 months after the
completion of treatment with resumption of follicular growth (indicated by regular
menses) in those with longer intervals and there was no apparent relationship
between increased follicle number/MFD and interval since treatment. The observed
differences between ABVD MFD and control data is between 9-21 standard
deviations (Figure 1C) and so a reduction in cortical volume would need to be of that
order of magnitude. There are no clinical data/observations to support such a degree
of shrinkage.

The underlying mechanism for an increase in MFD after ABVD treatment remains to
be established. An alternative explanation may be that this treatment has resulted in
new oocytes/follicles being formed. Putative germline stem cells or oogonial stem
cells, which may be capable of regenerating the NGF population under perturbed
conditions have been identified within the adult human ovary (White et
al., 2012; Dunlop et al., 2013; Hanna and Hennebold, 2014). It is possible that the
ABVD combination or specific components activate these cells to form oocytes or
oocyte like structures. Recent studies have shown that mesenchymal stem cells are
sensitive to bleomycin treatment (Nicolay et al., 2016) but nothing is known about
how these drugs affect putative germline stem cells and other ovarian cells.

We also observed that post-ABVD tissue contains follicle clusters, many containing
bi-ovular and binucleate follicles, a feature more commonly associated with the
prepubertal ovary (Anderson et al., 2014). Follicles with more than one oocyte are
reported during fetal development and in early life in many mammalian species
(Papadaki, 1978; Telfer and Gosden 1987; Silva-Santos and Seneda, 2011) but are
much rarer in adults (Turkalj et al., 2013) and may be preferentially lost with
abnormal follicles during childhood (Anderson et al., 2014). No bi-ovular or
binucleate follicles were observed in tissue from healthy women, or following OEPA-
COPDAC treatment, highlighting that this difference in NGF patterning in the cortex of
tissue is a result of the specific chemotherapy treatment. Furthermore, the in vitro
developmental potential of ABVD-treated tissue showed differences compared to control tissue, with limited follicle development, comparable to that from prepubertal girls (Anderson et al., 2014). We suggest that the lack of development in ABVD-treated tissue may be attributed to the inhibitory effect exerted by the high density of primordial follicles present (Da Silva-Buttkus et al., 2009). Initiation of follicle growth was observed in the obstetric patient cohort supporting the findings of previous studies (Anderson et al., 2014, McLaughlin et al., 2014).

In summary this study demonstrates that ABVD treatment does not diminish the ovarian reserve and may paradoxically increase it. Other significant features such as the presence of bi-ovular and binucleate oocytes and clustering are increased. In this respect, ABVD-exposed tissue is similar to that from prepubertal girls, and this similarity is also reflected in its reduced capacity for follicle development in vitro. The number of patients analysed is small and so interpretation should be cautious. However, the data presented here have highlighted a phenomenon that has not been previously reported. Further investigation is required to elucidate the mechanism by which the ovarian reserve is affected by ABVD treatment, and the consequences for later fertility and reproductive lifespan.

Acknowledgements

The authors wish to thank Anne Saunderson and Joan Creiger for patient recruitment, John Binnie for excellent technical assistance and all the patients who donated tissue.

Authors Roles:
Preparation of samples, experimental design, data collection and analysis, drafting the manuscript and approval of final version.

TWK Data analysis and interpretation, drafting the manuscript and approval of final version.

WHBW Acquisition of clinical data and interpretation, drafting the manuscript and approval of final version.

RAA Sample collection, acquisition of data and interpretation, drafting the manuscript and approval of final version.

EET Experimental design, analysis and interpretation, drafting the manuscript and approval of final version.

Funding

This work was supported by MRC grants G0901839 and MR/L00299X/1

Conflict of Interest

The authors have no conflicts of interest to declare
References


McLaughlin M, Telfer EE. Oocyte development in bovine primordial follicles is promoted by activin and FSH within a two-step serum-free culture system. *Reproduction* 2010;139:971-978.


Legends to Figures

Figure 1 (A). Observed and predicted human mean follicle density (MFD). Black dots represent model-predicted values from ages 10 through 50 years. Blue dots denote MFDs of patients that did not receive chemotherapy, green dots patients that received OEPA-COPDAC (combined vincristine, etoposide, prednisone, doxorubicin (OEPA) and cyclophosphamide, vincristine, prednisone, dacarbazine (COPDAC)) and red dots patients that received ABVD (adriamycin, bleomycin, vinblastine and dacarbazine). All tissue was uncultured. (B) Pearson product-moment correlation. The line of identity represents the idealised confluence of observed and predicted values. Blue dots indicate observed against predicted MFD for 3 untreated patients. (C) Bland-Altman Plot. The x-axis represents means (i.e. half the sum of observed and predicted MFD values); the y-axis represents the differences (i.e. predicted MFD values subtracted from observed values). The solid horizontal line shows no trend between means and differences. Blue dots denote difference from predicted MFD for untreated patients; these are between 0 and 1.25 standard deviations (i.e. between 0 and 16 follicles) below the zero predicted difference. Greens dots denote difference from predicted MFD for 3 OEPA-COPDAC-treated patients' chemotherapy protocol; these are between 1 and 11 standard deviations (i.e. between 12 and 132 follicles) below the zero predicted difference. The red dots denote difference from predicted MFD for 8 ABVD-treated patients; these are between 9 and 21 standard deviations (i.e. between 108 and 250 follicles) above the zero predicted difference.

Figure 2 (A) Distribution of follicle classes (as percentage of total) in fixed ovarian tissue from either untreated, OEPA-COPDAC (combined vincristine, etoposide, prednisone, doxorubicin (OEPA) and cyclophosphamide, vincristine, prednisone, dacarbazine (COPDAC)) or ABVD (adriamycin, bleomycin, vinblastine and...
Figure 3(A). Distribution of follicle classes (as percentage of total) in ovarian tissue cultured for 6 days from untreated (n=2) and ABVD (adriamycin, bleomycin, vinblastine and dacarbazine) treated girls and adults (n=4), and obstetric patients (n=10). Blue: non-growing follicles; red: primary follicles; green: secondary follicles. A total of 89, 614 and 274 follicles are classified in the three groups, respectively. (B) Photomicrograph of in vitro activated follicles in 23 year-old obstetric tissue. Scale bar 60µm. (C) Photomicrograph of non-growing follicles in 23 year-old ABVD-treated tissue after incubation for 6 days. Scale bar 60µm. (D) Photomicrograph showing immunohistochemical detection of DDX4 in 22 year old ABVD-treated ovarian cortex. (i) Brown staining indicating present in all structures morphologically identified as germ cells. (ii) Negative control where primary antibody was omitted. Scale bar = 60µm.

Figure 4 (A). Incidence (i.e. number of observations) of single (blue) and clustered (red) follicles as percentage of total in fixed ovarian tissue from untreated, OEPA-COPDAC(combined vincristine, etoposide, prednisone, doxorubicin (OEPA) and
cyclophosphamide, vincristine, prednisone, dacarbazine (COPDAC)) treated, ABVD
(adriamycin, bleomycin, vinblastine and dacarbazine)-treated girls and adults, and
obstetric patients. (B) Photomicrograph of non-growing follicles (NGFs) in fixed tissue
from 36 year-old obstetric tissue. Dashed blue lines indicating a distance of 
≤15µm between follicles. Scale bar 100µm. (C) Photomicrograph of non-growing
follicles in fixed tissue 22 year-old ABVD-treated tissue. Purple circles indicate areas
of clustered NGFs within 15µm or less of each other. Scale bar = 60µm. Inset: non-
growing bi-ovular follicle in ABVD-treated tissue. Scale bar 25µm in inset
Unable to Convert Image

The dimensions of this image (in pixels) are too large to be converted. For this image to convert, the total number of pixels (height x width) must be less than 40,000,000 (40 megapixels).
Table 1. Treatment regimen (ABVD (adriamycin, bleomycin, vinblastine and dacarbazine), or OEPA-COPDAC (combined vincristine, etoposide, prednisone, doxorubicin (OEPA) and cyclophosphamide, vincristine, prednisone, dacarbazine (COPDAC)), anti-Müllerian hormone (AMH) level and treatment to biopsy time interval of patients contributing tissue. All had Hodgkin’s lymphoma except the final one (aged 30) who had non-Hodgkin’s lymphoma.

<table>
<thead>
<tr>
<th>Age (years)</th>
<th>Treatment</th>
<th>AMH (pmol/L)</th>
<th>Treatment to Biopsy Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>none</td>
<td>&lt;4</td>
<td>n/a</td>
</tr>
<tr>
<td>14</td>
<td>OEPA COPDAC</td>
<td>not taken</td>
<td>9 months</td>
</tr>
<tr>
<td>15</td>
<td>OEPA COPDAC</td>
<td>not taken</td>
<td>6 months</td>
</tr>
<tr>
<td>15</td>
<td>none</td>
<td>&lt;4</td>
<td>n/a</td>
</tr>
<tr>
<td>16</td>
<td>OEPA COPDAC</td>
<td>10.1</td>
<td>6 months</td>
</tr>
<tr>
<td>16</td>
<td>ABVD</td>
<td>&lt;4</td>
<td>4 weeks</td>
</tr>
<tr>
<td>21</td>
<td>ABVD</td>
<td>not taken</td>
<td>4 weeks</td>
</tr>
<tr>
<td>22</td>
<td>ABVD</td>
<td>&lt;4</td>
<td>4 weeks</td>
</tr>
<tr>
<td>22</td>
<td>ABVD</td>
<td>&lt;4</td>
<td>6 months</td>
</tr>
<tr>
<td>23</td>
<td>ABVD</td>
<td>&lt;4</td>
<td>4 weeks</td>
</tr>
<tr>
<td>23</td>
<td>ABVD</td>
<td>&lt;4</td>
<td>4 weeks</td>
</tr>
<tr>
<td>25</td>
<td>ABVD</td>
<td>&lt;4</td>
<td>36 months</td>
</tr>
<tr>
<td>29</td>
<td>ABVD</td>
<td>not taken</td>
<td>6 weeks</td>
</tr>
<tr>
<td>30</td>
<td>none</td>
<td>not taken</td>
<td>n/a</td>
</tr>
</tbody>
</table>
Table 2. Number of follicles and non-growing follicles (NGFs) analysed in ovarian cortical tissue of Hodgkin lymphoma (HL), non-Hodgkin lymphoma (NHL) and obstetric patients undergoing elective caesarean section (ECS). HL and NHL patients either received adriamycin, bleomycin, vinblastine and dacarbazine (ABVD) or combined vincristine, etoposide, prednisone, doxorubicin (OEPA) and cyclophosphamide, vincristine, prednisone, dacarbazine (COPDAC) OEPA-COPDAC or no treatment (Nil) prior to biopsy collection.

<table>
<thead>
<tr>
<th>Diagnosis</th>
<th>Age (Years)</th>
<th>Treatment</th>
<th>Vol mm³ Analysed</th>
<th>Total No. follicles</th>
<th>Total No. NGFs</th>
<th>NGFs/mm³</th>
</tr>
</thead>
<tbody>
<tr>
<td>HL</td>
<td>12</td>
<td>Nil</td>
<td>0.92</td>
<td>195</td>
<td>187</td>
<td>203</td>
</tr>
<tr>
<td>HL</td>
<td>15</td>
<td>Nil</td>
<td>1.7</td>
<td>259</td>
<td>194</td>
<td>114</td>
</tr>
<tr>
<td>NHL</td>
<td>30</td>
<td>Nil</td>
<td>0.9</td>
<td>15</td>
<td>15</td>
<td>17</td>
</tr>
<tr>
<td>HL</td>
<td>14</td>
<td>OEPA-COPDAC</td>
<td>1.8</td>
<td>19</td>
<td>19</td>
<td>10.5</td>
</tr>
<tr>
<td>HL</td>
<td>15</td>
<td>OEPA-COPDAC</td>
<td>5.84</td>
<td>732</td>
<td>605</td>
<td>103</td>
</tr>
<tr>
<td>HL</td>
<td>16</td>
<td>OEPA-COPDAC</td>
<td>2.14</td>
<td>152</td>
<td>86</td>
<td>40</td>
</tr>
<tr>
<td>HL</td>
<td>16</td>
<td>ABVD</td>
<td>4.75</td>
<td>988</td>
<td>988</td>
<td>208</td>
</tr>
<tr>
<td>HL</td>
<td>21</td>
<td>ABVD</td>
<td>1.53</td>
<td>473</td>
<td>464</td>
<td>303</td>
</tr>
<tr>
<td>HL</td>
<td>22</td>
<td>ABVD</td>
<td>2.66</td>
<td>605</td>
<td>599</td>
<td>225</td>
</tr>
<tr>
<td>HL</td>
<td>22</td>
<td>ABVD</td>
<td>1.64</td>
<td>444</td>
<td>437</td>
<td>266</td>
</tr>
<tr>
<td>HL</td>
<td>23</td>
<td>ABVD</td>
<td>2.41</td>
<td>712</td>
<td>660</td>
<td>273</td>
</tr>
<tr>
<td>HL</td>
<td>23</td>
<td>ABVD</td>
<td>2.6</td>
<td>558</td>
<td>506</td>
<td>194</td>
</tr>
<tr>
<td>HL</td>
<td>25</td>
<td>ABVD</td>
<td>3.06</td>
<td>642</td>
<td>617</td>
<td>201</td>
</tr>
<tr>
<td>HL</td>
<td>29</td>
<td>ABVD</td>
<td>3.62</td>
<td>579</td>
<td>578</td>
<td>160</td>
</tr>
<tr>
<td>ECS</td>
<td>23</td>
<td>N/A</td>
<td>1.21</td>
<td>38</td>
<td>32</td>
<td>26</td>
</tr>
<tr>
<td>ECS</td>
<td>24</td>
<td>N/A</td>
<td>1.45</td>
<td>85</td>
<td>73</td>
<td>50</td>
</tr>
<tr>
<td>ECS</td>
<td>26</td>
<td>N/A</td>
<td>2.01</td>
<td>77</td>
<td>63</td>
<td>32</td>
</tr>
<tr>
<td>ECS</td>
<td>28</td>
<td>N/A</td>
<td>2.28</td>
<td>67</td>
<td>51</td>
<td>22</td>
</tr>
<tr>
<td>ECS</td>
<td>28</td>
<td>N/A</td>
<td>1.06</td>
<td>60</td>
<td>49</td>
<td>46</td>
</tr>
<tr>
<td>ECS</td>
<td>31</td>
<td>N/A</td>
<td>2.72</td>
<td>39</td>
<td>38</td>
<td>14</td>
</tr>
<tr>
<td>ECS</td>
<td>33</td>
<td>N/A</td>
<td>2.31</td>
<td>34</td>
<td>29</td>
<td>12.5</td>
</tr>
<tr>
<td>ECS</td>
<td>33</td>
<td>N/A</td>
<td>1.98</td>
<td>36</td>
<td>26</td>
<td>13</td>
</tr>
<tr>
<td>ECS</td>
<td>36</td>
<td>N/A</td>
<td>1.55</td>
<td>17</td>
<td>14</td>
<td>9</td>
</tr>
<tr>
<td>ECS</td>
<td>36</td>
<td>N/A</td>
<td>2.39</td>
<td>15</td>
<td>15</td>
<td>6</td>
</tr>
<tr>
<td>ECS</td>
<td>36</td>
<td>N/A</td>
<td>2.71</td>
<td>22</td>
<td>12</td>
<td>4</td>
</tr>
<tr>
<td>ECS</td>
<td>39</td>
<td>N/A</td>
<td>1.32</td>
<td>14</td>
<td>11</td>
<td>8</td>
</tr>
</tbody>
</table>