CANCER GENOMICS & PROTEOMICS *4*: 175-186 (2007)

Review

Tailoring Targeted Therapy to Individual Patients: Lessons to be Learnt from the Development of Mitomycin C

MILÈNE VOLPATO and ROGER M. PHILLIPS

Institute of Cancer Therapeutics, University of Bradford, Bradford BD7 1DP, U.K.

Abstract. *The modern era of targeted therapeutics offers the potential to tailor therapy to individual patients whose tumours express a specific target. Previous attempts to forecast tumour response to conventional chemotherapeutics based on similar principles have however been disappointing. Mitomycin C (MMC), for example, is a bioreductive drug that requires metabolic activation by cellular reductases for activity. The enzyme NAD(P)H:Quinone oxidoreductase-1 (NQO1) can reduce MMC to DNA damaging species but attempts to establish the relationship between tumour response to MMC and NQO1 expression have generated conflicting reports of good and poor correlations. Several other reductases are known to activate MMC. This, in conjunction with the fact that various physiological and biochemical factors influence therapeutic response, suggests that the mechanism of action of MMC is too complex to allow tumour response to be predicted on the basis of a single enzyme. Alternative approaches using more complex biological and pharmacological systems that reflect the spectrum of reductases present within the tumour have been developed and it remains to be seen whether or not the predictive value of these approaches is enhanced. With regards to targeted therapeutics, the experience with MMC suggests that prediction of tumour response based on analysis of a single target may be too simplistic. Multiple mechanisms of action and the influence of tumour microenvironment on cell biology and drug delivery are likely to influence the final outcome of therapy. The challenge for the future progression of this field is to develop assays that reflect the overall biological and pharmacological processes involved in drug activation whilst retaining the simplicity and robustness required for routine chemosensitivity testing in a clinical setting.*

The ability to tailor chemotherapy to individual patients who are most likely to benefit from treatment has been a major objective in cancer research for many years. Since the seminal studies of Hamburger and Salmon in the late 1970's where primary cell cultures and clonogenic assays were used (1), numerous approaches have been evaluated. Despite extensive research, the ability to accurately forecast the response of individual patients to chemotherapy remains elusive. The modern era of targeted therapeutics offers enhanced prospects of individualised therapy. The development of trastuzumab for use against HER-2 positive breast cancers is a good example of this (2, 3). Whilst the example of trastuzumab represents a significant step forward individualised therapy, is it realistic to expect that all tumours that express a specific target will respond to target orientated therapies? Even in the case of trastuzumab, tumour response remains heterogeneous with some patients responding well whereas others are inherently resistant to treatment (4). Numerous attempts have been made to predict the response of tumours to conventional cytotoxics using similar approaches. However, no reliable assay is currently in routine clinical use. In this article, the predictive value of assays designed to forecast the response of tumours to mitomycin C (MMC, Figure 1) will be critically reviewed. The rationale for selecting MMC is that it is a targeted anticancer agent and extensive efforts have been made to predict tumour response based upon analysis of key enzymes involved in its mechanism of action. The principle objective of this review is to obtain an understanding of why previous approaches have been unsuccessful in the belief that this may inform the design of predictive assays for targeted therapeutics.

Abbreviattions: MMC: Mitomycin C; NQO1: NAD(P)H:Quinone oxidoreductase-1; ROS: reactive oxygen species; SNP: single nucleotide polymorphism; 2,7-DAM: 2,7-diaminomitosene; BSO: L-buthionine-R,S-sulfoximine.

Correspondence to: Milène Volpato, Institute of Cancer Therapeutics, University of Bradford, Bradford BD7 1DP, U.K. Tel: +44 1274 233226, Fax: +44 1274 233234, e-mail: m.volpato@bradford.ac.uk

Key Words: Superficial bladder cancer, mitomycin C, NQO1, targeted therapeutics, bioreductive drugs, review.

MMC and the Potential for Tailored Therapy

MMC is a naturally occurring antibiotic that was isolated from *Streptomyces caespitosis* in 1956 by Hata *et al.* (5). It belongs to a class of anticancer agents known as bioreductive drugs and it is regarded as the prototypical bioreductive drug (6). MMC is a clinical component of combination chemotherapy regimens used to treat a range of tumour types (7). Throughout Europe, MMC is routinely used as a single agent to treat superficial bladder cancers and it significantly delays tumour recurrence (8, 9). The response of superficial bladder cancers to MMC is heterogeneous (10). So there is a clinical need to identify patients that are most likely to benefit from treatment.

In general terms, bioreductive drugs are molecules that require metabolic activation by cellular reductases to generate metabolites that damage DNA. They were initially developed to target hypoxic cells and selectivity was determined by the ability of oxygen to reverse the activation process (11, 12). As our understanding of the enzymatic activation processes increased, it became clear that certain bioreductive drugs can also target aerobic cells (13). In this case, selectivity is determined primarily by the presence of elevated levels of reductase activity in tumour tissue (13). This generated the concept of 'enzyme directed bioreductive drug development', an integral component of which is the ability to forecast tumour response based upon knowledge of the activity of specific reductases and/or the extent of tumour hypoxia (14). Whilst conceptually elegant, its ultimate value depends upon a number of conditions. The main requirement is that one enzyme plays a dominant role in bioreductive activation and that tumour response is determined by the expression of this enzyme in tumours. Furthermore, it also assumes that cells ability to respond to DNA damage (DNA repair or ability to undergo apoptosis) play a comparatively minor role in determining response. The ability to predict tumour response based upon analysis of a single enzyme and approaches that challenge the assumptions outlined above will, therefore, be the initial focus of this review.

MMC and its Mechanism of Action

The mechanism of action of MMC has been extensively studied and reviewed elsewhere (15-18). Briefly, the initial and critical step in the bioactivation process is reduction of the quinone to either the semiquinone or the hydroquinone by one- or two-electron reductases, respectively (Figure 1). In the presence of oxygen, the semiquinone enters into a redox cycle that produces reactive oxygen species (ROS) which can lead to DNA damage. It is generally acknowledged, however, that the DNA damage caused by ROS contributes little to the overall cytotoxicity of MMC

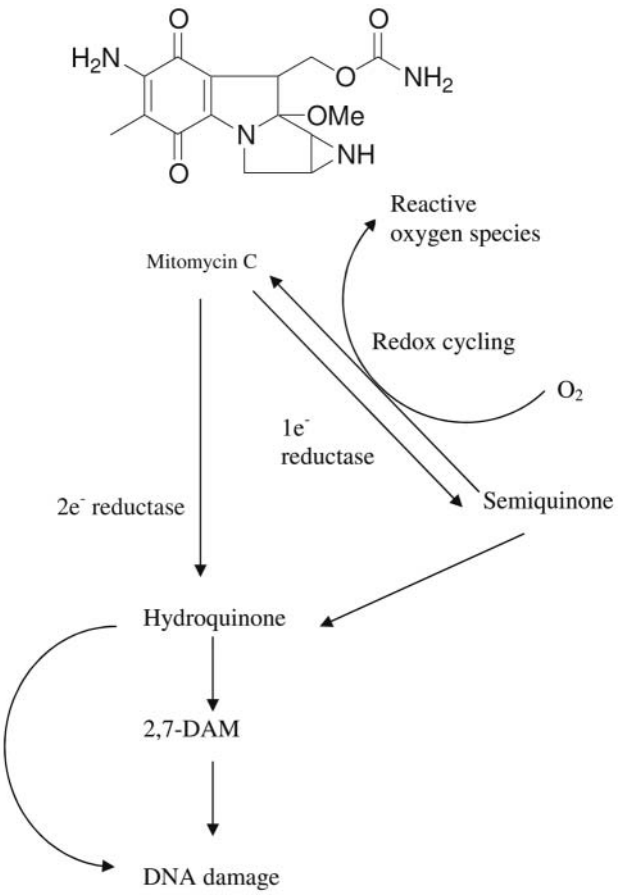

Figure 1. *Basic schematic of MMC bioactivation. For a more complete overview of the full metabolic route, see Cummings et al. (17).*

compared to DNA alkylation (19, 20). Under hypoxic conditions, the semiquinone free radical chemically rearranges into the more stable hydroquinone which undergoes a series of chemical reactions leading ultimately to alkylation of DNA (21). When the hydroquinone species are generated directly by 2 electron reductases (by passing the semi-quinone), the generation of alkylating species is not dependent upon the presence or absence of oxygen. The covalent DNA adducts produced are predominantly formed at the N2 position of guanine (but also at the N7 position) and both intra-strand and inter-strand crosslinks as well as mono-adducts are produced. It is however the interstrand cross links rather than the monoadducts that are critical factors in determining cell death (22).

Physiological conditions, such as low pH (23, 24) and oxygen tension (25, 26) can have a significant influence on cellular response to MMC but the key step in the process remains the initial reduction of the quinone nucleus by one and/or two electron reductases. Numerous enzymes have been implicated in the reduction of MMC. These include cytochrome P450 reductase (27), xanthine dehydrogenase

(28), xanthine oxidase (29, 30), NADPH ferredoxin reductase (31), cytochrome b5 reductase (32), an uncharacterised cytosolic enzyme (15, 33), glucose regulatory protein 58 (34, 35), HAP1 (35), NQO1 (36) and more recently NAD(P)H:Quinone oxidoreductase 2 (37, 38). Whilst MMC is a substrate for many enzymes, attention has predominantly focused on NQO1 (17, 18, 39) and the relationship between NQO1 and response to MMC has been extensively studied. In addition to enzymatic reduction, a series of other events should be taken into consideration as these may also determine cellular response. These are summarised in simplified form in Figure 2 and include; reduction of MMC by reductases and other metabolic routes such as detoxification pathways, the formation of DNA damage and its repair, and finally the induction of cell death. Similar reasoning could be extended to other forms of targeted therapy in terms of the presence of an active target, the target/drug interaction, the effect of this interaction (*e.g.* activation or repression of a signalling pathway, tubulin disruption) and the induction of cell death. Each step of this process may be of importance in predicting response to treatment and will be commented upon in this review. Initially however, the relationship between NQO1 and response to MMC will be discussed.

Role of NQO1 in MMC Bioactivation and the Prospect of Individualising Therapy Based on NQO1 Expression

NQO1 is a cytosolic flavoprotein that catalyses the two-electron reduction of a broad range of substrates (particularly quinone based compounds) using NADH or NADPH as the source of electrons (18, 40, 41). Several possible physiological functions for NQO1 have been proposed (42, 43) although historically, its role in protecting cells from highly reactive environmental and synthetic quinones is believed to be its principle function. This is achieved by converting quinones directly into redox stable hydroquinones, thereby bypassing the semi-quinone free radical and subsequent generation of ROS caused by redox cycling in air. The newly formed hydroquinones can be conjugated to glucoronides or sulfides, resulting in increased water solubility and excretion (44). In the case of certain quinones however, the hydroquinone may itself autoxidise to generate ROS or directly alkylate DNA. In these cases, reduction by NQO1 represents a pro-drug activation mechanism. The decision as to whether a compound is detoxified or activated by NQO1 is determined largely by the chemistry of the groups attached to the quinone nucleus (44). In the case of MMC, it is a substrate for NQO1 and reduction by NQO1 results in DNA alkylation in cell free assays (36, 45, 46). This fact alone suggests that NQO1 could play a significant role in determining therapeutic response.

Two additional pieces of evidence significantly enhanced the prospect of predicting response to MMC based on analysis of NQO1. First, a series of studies demonstrated that the expression of NQO1 (at the mRNA and protein level) was not only elevated in several tumour types but that within each pathological group of tumours, wide interpatient heterogeneity existed (47-49). Some patient's tumours expressed high levels of NQO1 activity whereas others were devoid of activity, making it was conceivable that heterogeneity in tumour response to MMC could be related to heterogenous NQO1 expression. Second, the gene encoding for NQO1 is polymorphic and two single nucleotide polymorphic (SNP) variants (C609T [NQO1*2] and C465T [NQO1*3]) are associated with total loss or significant reductions in NQO1 activity (50-53). In view of the fact that NQO1 can activate MMC, wide variations in NQO1 activity or the presence of SNP's leading to reduced NQO1 activity could have a significant bearing on therapeutic outcome (41). It should be stressed however that the ability of NQO1 to reduce MMC is not simple as it only occurs under mild acidic conditions (45). At physiological pH values, MMC is not only a poor substrate for NQO1 but actually inhibits NQO1 activity (23, 45, 54). Whilst tumours are known to contain regions of low extracellular pH 55, intracellular pH is generally maintained at or slightly above neutrality (56). These findings may impact on the relevance of NQO1 as a major determinant of MMC activity as discussed below.

Relationship between NQO1 and Response to MMC *In Vitro*

As stated previously, the existence of a correlation between reductase expression (mRNA and/or protein) and treatment response is an essential requirement for enzyme directed drug development. Several experimental approaches have been employed but as described below, conflicting reports of good and poor correlations between NQO1 expression and response *in vitro* can be found within the available literature. In studies using panels of cell lines that inherently express a broad range of NQO1 mRNA and/or protein, reports of good correlations between NQO1 activity and response (57-61) contrast sharply with reports of poor correlations (15, 62-64). Similarly, enhanced activity of MMC has been observed by some groups in isogenic cell lines where NQO1 has been over expressed (65-68) whereas other laboratories have demonstrated that MMC sensitivity is independent of NQO1 activity in similar models (15, 69, 70). Several studies using cell lines that are resistant to MMC have demonstrated that NQO1 activity is reduced compared to the parental lines (58, 71). Other studies have demonstrated that cisplatin resistant A2780 cells (which have elevated levels of NQO1) are also resistant to MMC,

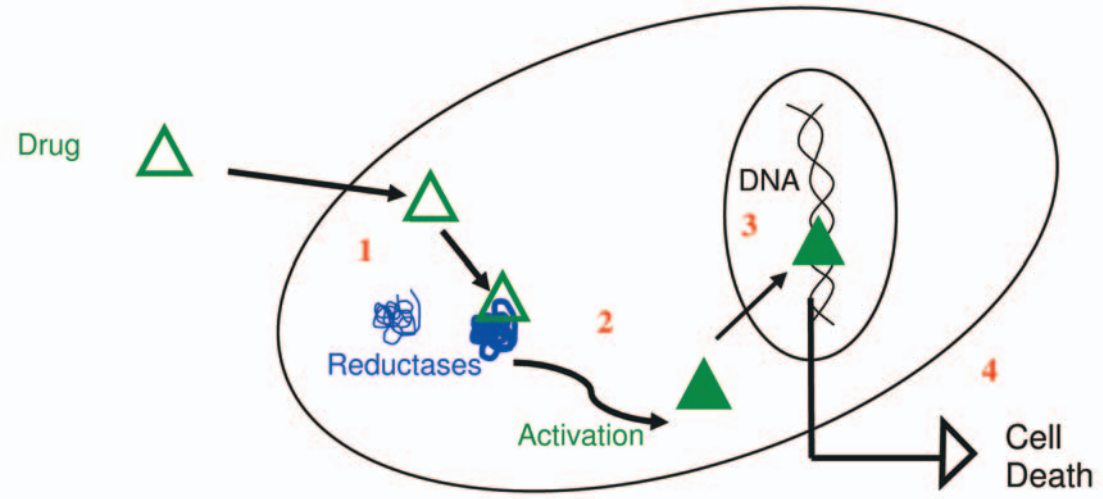

Figure 2. *Simplified cartoon outlining the key steps required for cellular response to MMC. 1; presence of reductases/target protein, 2; MMC metabolism or drug/target interaction, 3; DNA damage or effect of target disruption, 4; Cell death induction.*

which suggests that other factors influence the outcome of MMC treatment (72). Attempts to chemically modulate NQO1 activity in cell lines, using the inhibitor dicumarol for example, have suggested that NQO1 plays a role in activating MMC (73, 74). Similarly, NQO1 activity can be induced in cells and enhanced toxicity to MMC has been observed following NQO1 induction by 1,2-dithiole-3-thione, dimethyl fumarate and arsenite (75-77). However, caution needs to be exercised in the interpretation of these experiments as dicumarol is not a selective inhibitor of NQO1 (78) and the recent finding that NQO1 can stabilise p53 (79, 80) suggest that manipulation of NQO1 levels in cells could potentially modulate therapeutic response to DNA damage.

The majority of the studies mentioned above have focused on the relationship between NQO1 and response to MMC under aerobic conditions but the situation becomes more complex when similar experiments are conducted under hypoxic conditions. The determination of hypoxic cytotoxicity ratios (HCR; defined as the ratio of IC_{50} values in air divided by IC_{50} values under hypoxia) is a commonly used method to compare the activity of drugs under both aerobic and hypoxic conditions. In the case of MMC, high HCR values have been reported in cell lines that have low or no NQO1 activity (26, 81). In NQO1 rich cells, HCR values are typically very low, indicating that these cells are equally sensitive to MMC in the presence and absence of oxygen (26, 82). Whilst the mechanistic basis for these observations is not fully understood, these results present a significant additional challenge to predictive drug testing for MMC sensitivity based on the analysis of NQO1 alone.

With regards to the potential impact of NQO1 SNP's on MMC sensitivity, resistance to MMC has been demonstrated in a number of cell lines that are homozygous for the NQO1*2 allele (53, 83). Similarly for the NQO1*3 allele, cells are more resistant to MMC than wild-type cells (84, 85). Furthermore, the response of primary cell lines derived from gastric tumours to MMC was dependent upon NQO1 genotype, with increased sensitivity to MMC observed in cells with wild-type NQO1 (86). In contrast to studies based on NQO1 phenotypic expression or activity, no studies have been published that contradict these findings and experimentally at least, genotype status provides the strongest evidence that NQO1 plays a role in determining therapeutic outcome to MMC treatment.

Relationship between NQO1 and Response to MMC in Xenografts and Patients

The ability to predict response to MMC based upon analysis of NQO1 phenotype and genotype has been critically addressed in a series of *in vivo* and clinical studies. With regards to NQO1 phenotype, a good correlation between MMC sensitivity *in vivo* and NQO1 activity was reported in a panel of eight non-small cell and small cell lung tumour xenografts (48). In other studies, however, a poor correlation between anti-tumour activity and NQO1 levels has been reported (87-89). In an extensive panel of 45 human tumour xenografts expressing a broad spectrum of NQO1 enzyme activity, no correlation was observed between NQO1 activity and response to MMC *in vivo* (64). In clinical studies, promising results were obtained by Gan *et al.* where the response of histocultures derived from 21 human bladder

cancer patients (with both superficial and invasive disease) correlated with the mRNA expression of NQO1 and cytochrome P450 reductase (90). In contrast, NQO1 protein expression as measured by immunohistochemistry in 92 superficial bladder cancers (pathology was restricted to G1/G2 and pTa/T1 tumours) did not correlate with clinical response to MMC in terms of time to first recurrence (91).

With regards to the polymorphic variants of NQO1, a study by Fleming *et al.* reported that in 117 patients with disseminated peritoneal cancer treated with intraperitoneal hyperthermic MMC, patients that were heterozygous or homozygous with respect to NQO1*2 had reduced survival compared to patients genotyped as wild-type (92). This very significant finding suggested for the first time that screening for this polymorphism may be useful in identifying individuals who may be at risk of treatment failure following intraperitoneal MMC therapy. In contrast to these encouraging reports, studies in both human tumour xenografts (93) and superficial bladder cancer patients (94) have demonstrated that genotyping individuals with respect to the NQO1*2 SNP did not correlate with therapeutic outcome.

In summary, the ability to forecast the response of tumours based on the levels of NQO1 or NQO1 genotype status is unlikely to be of practical value in the clinic. Whilst some evidence of positive correlations have been reported, there is a wealth of conflicting data in the literature which suggests otherwise. A number of other enzymes have been implicated in the activation of MMC and some attempts have been made to correlate their expression status, sometimes in conjunction with the NQO1 levels, with response to MMC treatment. It remains to be seen whether the response of tumours to MMC can be forecast based on the expression of these enzymes but, the complexity of MMC activation suggests that this approach is unlikely to be productive. Models or assays that mimic more closely the complexity of the biological system offer a potential way forward and some of these approaches are discussed in the following sections.

Analysis of MMC Metabolism in Crude Tumour Homogenates; Relationship with Cellular and Tumour Response to MMC

As multiple enzymes are involved in the activation of MMC, Cummings *et al.* proposed an alternative approach based upon the ability of tumour homogenates to metabolically activate MMC (17). This represented the first move from single enzyme/marker prediction to multiple enzyme activity assessment and it is based on the rationale that tumour homogenates will contain a 'cocktail' of reductases capable of activating MMC. By using analytical techniques identifying active metabolites, a more accurate assessment of a tumour's ability to activate MMC may therefore be achieved (17). Initial studies focused on the identification of 2,7-diaminomitosene (2,7-DAM) as an indicator of bioreductive activation. 2,7-DAM is a transient intermediate formed after the reduction of MMC and it is used as a marker of drug activation (Figure 1). In two murine colon carcinoma models (MAC 16 and MAC 26) 2,7-DAM was readily detected in tumours following intra-tumoral injection of MMC (15). However, higher levels of 2,7-DAM were detected in the comparatively more resistant MAC 26 tumour model compared to MAC 16 tumours, indicating that other pharmacological factors have a significant influence of therapeutic outcome. The analysis of 2,7-DAM is however technically challenging as it is a reactive metabolite that readily binds covalently to cellular macromolecules and once bound, it will be invisible to the majority of analytical techniques.

In an attempt to circumvent this issue, studies conducted in our laboratory analysed the ability of tumour homogenates from a panel of resistant and sensitive human tumour xenografts to metabolise MMC (64). The rate of metabolism of the parent MMC compound was significantly greater in the MMC sensitive group ($t_{½}$=75±48.3 min, n=6) compared to the resistant group ($t_{½}$=280±129.6 min, n=11). Based upon these results, a pilot study was established in 30 patients with superficial (G1/G2 and pTa/T1) bladder cancer where surgical specimens were immediately flash frozen in liquid nitrogen and transferred to the laboratory. Using identical methodologies to our previous studies (64), this study demonstrated that the ability of tumour homogenates to metabolise MMC varied considerably between individual tumours with half lives ranging from 17.5 min to >1000 min (Figure 3).

The key question was whether or not these inherent differences in the ability of tumours to metabolise MMC translates into differences in therapeutic response. Following tumour resection, each patient received a single dose of MMC (40 mg/40 ml) administered intravesically within 24 hours of surgery and time to first recurrence was determined by established follow up procedures. No trend could be established between either metabolism rates and time to first recurrence or metabolism rates and the presence or absence of recurrent disease at the time of survey. Surprisingly, some tumours that slowly metabolised MMC *in vitro* responded as well to MMC as tumours that rapidly metabolised MMC (patients A and B, Table I). Within the G2/pTa tumours, 3 patients suffered recurrence following MMC therapy. Patients C and D, had similar clinical response (first recurrence 3 months after MMC therapy) despite the fact that tumour homogenate from patient C metabolised MMC rapidly ($t_{1/2}$=17.5 min) whereas tumour homogenate from patient D metabolised MMC more slowly ($t_{1/2}$=395 min) (Table I). The observation that several of the tumours that

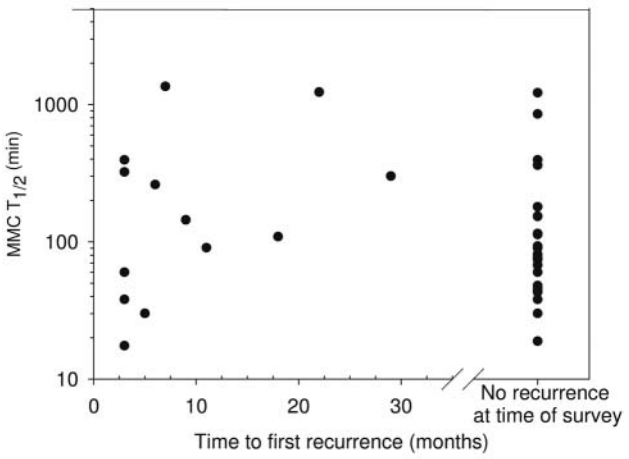

Figure 3. *Relationship between MMC metabolism by bladder tumour homogenates and clinical response to MMC. Protein homogenates (10 mg/ml) were then incubated at 37˚C in the presence of 2 mM NADH and 2 mM NADPH and the reaction was initiated by the addition of MMC (200 μM). At various time intervals, 30 μl of the reaction mixture was removed and added to 90 μl of acetonitrile containing the internal standard, porfiromycin (PFC, 50 μM). Samples were evaporated and resuspended in mobile phase. Chromatographic separation of MMC by HPLC has been described previously (64). Detection of MMC is performed at 365 nm and 310 nm with a flow rate of 1 ml/min. The half-life of MMC was determined from least squares log linear regression analysis $t_{1/2}$=0.693/Kd where Kd is the decay rate constant (the slope of the regression analysis x 2.303).*

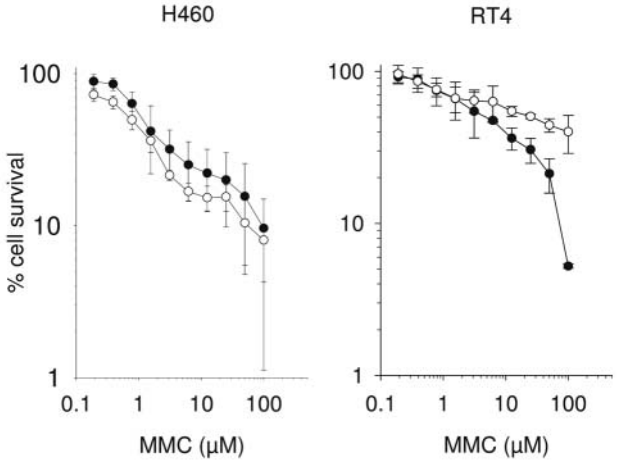

Figure 4. *The influence of the glutathione detoxification pathway on MMC cytotoxicity in human cancer cell lines. The effect of the glutathione detoxification pathway was evaluated, using BSO, an inhibitor of glutathione synthesis, reported to be effective when used at 50 μM for 24 h (118). Cells were plated into 96 well culture plates incubated overnight. The following day, cells were incubated with BSO (50 μM) or fresh medium for 24 h. Cells were then exposed to a range of MMC concentrations (0.2 μM to 100 μM) for 1 h in absence of BSO, after which they were washed twice with HBSS prior to addition of complete media. Cell survival was assessed using the MTT assay. IC_{50} values are expressed in terms of the mean±standard deviation for three independent experiments. MMC cytotoxicity in H460 and RT4 cells pre-treated with 50 μM BSO (●) for 24 h or in absence of BSO (○). Each data point represents the mean±SD for 3 independent experiments.*

Table I. *MMC half-life and clinical response obtained for 4 superficial bladder cancer patients treated with MMC. These patients were selected to illustrate the extremes of both clinical response to MMC and MMC metabolic rates.*

Patients	Tumour grade	MMC half-life (min)	Time to first recurrence (month)
A	G1/pTa	93	>27
B	G1/pTa	853	>24
C	G2/pTa	17	3
D	G2/pTa	395	3

metabolised MMC slowly responded well to treatment (Table I) implies that only a small fraction of MMC is needed to be activated to DNA damaging species or that the tumour cells themselves are exquisitely sensitive to low levels of DNA damage. On the other hand, several tumours were able to metabolise MMC rapidly but failed to respond well to treatment (Table I). This suggests that metabolism of MMC is not only a reflection of bioreductive activation but also of other metabolic routes such as detoxification pathways.

The glutathione-glutathione S transferase pathway is a known resistance mechanism for MMC (95). To exemplify this, additional studies in our laboratory have analysed the effect of glutathione depletion by the non-toxic agent L-buthionine-R,S-sulfoximine (BSO) on *in vitro* chemosensitivity to MMC. The IC_{50} obtained after treatment of H460 cells with BSO for 24 hours (50 μM) followed by exposure to a range of MMC concentrations for 1 hour, were 1.45±0.91 μM, compared to 0.77±0.28 μM in the absence of BSO (Figure 4). In contrast, exposure of RT4 cells to BSO prior to MMC treatment induced a 6.5-fold decrease in the IC_{50}, from 30.20±7.33 μM down to 4.62±3.80 μM (Figure 4). These results suggested that inherent differences in detoxification pathways (*e.g.* glutathione) existed between RT4 and H460 cells that could have had a significant bearing on MMC sensitivity.

In summary, whilst significant differences exist in the ability of tumours to metabolise MMC, the lack of correlation between metabolic rates and tumour response suggests that this approach needs to be refined. The ability to measure active metabolites, the role of detoxification pathways and the destruction of tumour microenvironments during the preparation of homogenates represent significant obstacles that would have to be addressed.

Induction and Response to DNA Damage as an Indicator of MMC Sensitivity

Developing the approach outlined by Cummings *et al.* (17), analysis of DNA damage induction in tumour cells would represent not only the end product of bioreductive activation by multiple enzymes but would also take into account the role played by detoxification pathways and other protein/drug interaction. Analysis of DNA damage induction may therefore provide an indication of bioreductive activation. As mentioned previously and discussed in detail elsewhere (16, 17, 22), MMC induces a range of DNA lesions but inter-strand cross links are regarded as the major cytotoxic lesions (22). In a panel of human tumour cell lines, *in vitro* chemosensitivity to MMC correlated well with the induction of DNA inter-strand crosslinks as measured by the comet assay (96). This study demonstrated that analysis of DNA interstrand crosslink formation provides a good indicator of MMC chemosensitivity *in vitro* and further studies are required to assess the relationship between DNA interstrand cross link formation and response to MMC *in vivo* (96).

Two other factors need to be taken into consideration in view of these findings; the ability of cells to repair DNA damage and the response of cells to DNA damage in terms of their ability to undergo apoptosis. With regards to DNA repair, full details of the mechanism of DNA repair of MMC induced DNA damage remains unclear but it involves multiple repair pathways including nucleotide excision repair, homologous recombination repair and translesion bypass repair pathways (97, 98). In contrast to the relationship between interstrand crosslink formation and response, poor correlations between response and DNA repair kinetics (determined by the comet assay) and apoptosis induction (determined by Annexin V-FITC/PI dual staining and Hoescht 33342 staining) were observed (96). Whilst DNA repair processes can generally influence therapeutic response, the data presented in this study suggests that it plays a minor role in determining response to MMC. These findings were in agreement with similar studies analysing the role played by DNA repair in determining response to radiotherapy were no correlation could be established between the two parameters *in vitro* (99-101) and in patients with acute myeloid leukaemia (102). In terms of apoptosis induction, conflicting reports of the relevance of apoptosis to MMC sensitivity have been published. Some studies showed a trend between response to MMC and the levels of apoptosis measured in cell lines and in bladder tumours exposed the drug *ex vivo* (103, 104), whereas other reports showed a lack of correlation between the two parameters (105-108). The latter were in accordance with a review by Okada and Mak describing how DNA damage could trigger processes of senescence or mitotic catastrophe rather than programmed cell death (109). However, a recent study which used 20 non small cell lung carcinoma samples suggested the existence of a relationship between the levels of apoptosis induced by *ex vivo* exposure to MMC, cisplatin and taxotere and reduced metabolic activity in the cultured samples (110). They highlighted the usefulness of measuring pharmacodynamic parameters of tumour mass cultured and treated *ex vivo* in order to predict response (110).

The correlation observed between inter-strand crosslink formation and response suggested that the process of bioreductive activation remains the major determinant of cellular response to MMC at least *in vitro* and further studies are required to determine whether or not the comet assay can accurately forecast the response of tumours to MMC *in vivo*. The comet assay encompasses the key principles developed above in that it is a cell based assay where bioreductive activation processes take place alongside detoxification pathways in a competitive manner. Recent studies have also demonstrated that the comet assay provides a good indication of response to radiotherapy, is simple, inexpensive, rapid and requires small biopsy samples (99-101, 111). It remains to be seen whether or not the comet assay can be used to accurately forecast the response of superficial bladder cancers to MMC.

Conclusion

Two main issues arise from this review. The first relates to the prospects for developing predictive assays for MMC and the second is what lessons can be drawn from MMC that can or should be considered when developing predictive assays for targeted therapies.

With regards to MMC specifically, there is sufficient uncertainty and conflict in the literature to indicate that analysis of NQO1 alone is unlikely to be beneficial in terms of predicting response. Whether correlations can be obtained between the expression of other reductases involved in MMC activation and response remains to be seen but the complexity of MMC's mechanism of action would suggest that this approach is unlikely to be productive. Cell based assays are a promising way forward as they retain a degree of complexity within the system but this may be compromised by the fact that disruption of solid tumours would also destroy local tumour microenvironments that can influence the activity of MMC. Exposure of biopsies to MMC prior to disaggregating the tissue may circumvent this although this introduces additional problems concerning drug delivery and changes in microenvironmental conditions during drug exposure. Significant obstacles therefore exist in relation to solid tumours and systemic treatments but in the case of superficial bladder cancer, the prospect of developing predictive assays is more promising. As mentioned

previously, MMC is used as a single agent to treat superficial bladder cancer and this simplifies the assessment of clinical response compared to other tumours where MMC is used in combination with other cytotoxics. It is typically administered intravesically within 24 hours of surgery and this provides two key benefits. First, this route of drug administration reduces pharmacokinetic variations in drug exposure parameters compared to the wide inter-patient variations typically observed following systemic or oral administration. Second, the removal of the solid tumour mass effectively removes any complications caused by microenvironmental conditions. In addition, the comet assay is relatively rapid and from a logistical point of view, it should be feasible to obtain data within the 24 hour window between surgery and chemotherapy. Future studies will determine whether the comet assay or conceptually similar approaches have predictive value in the clinic.

With regards to the second issue, there are similarities between MMC and current approaches used to develop predictive assays for targeted therapies. The most obvious of which is the use of single markers to identify those patients whose tumours are most likely to respond. As described above, the prospects of predicting tumour response to MMC based upon analysis of a single enzyme are poor, which raises the question of whether or not similar mistakes are being made with the new generation of targeted therapies? As in the case of enzyme directed bioreductive drug development, the underlying principle is that if a tumour expresses the target, then that tumour should respond. If this is to be successful, the drug should be specific for its target. Once the drug/target interaction has occurred, downstream events leading to a therapeutic response should be the same within a specific cancer type. Whilst modern target orientated therapies are likely to have a much simpler mechanism of action than MMC, it is generally accepted that the majority of small molecule therapeutics have multiple targets. In the case of Imatinib for example, this compound was designed to inhibit tyrosine kinase activity of the BCR-Abl protein produced by a single genetic event in chronic myelogenous leukaemia. Subsequent studies however demonstrated that imatinib is also active against gastrointestinal stromal tumours that harbour mutations in KIT (112). This illustrates the point that even with targeted drugs, multiple targets and mechanisms of action exist.

Once the drug has bound or interacted with its target, will this ultimately lead to a therapeutic response in all circumstances? The tumour microenvironment is known to influence therapeutic outcome and it is associated with resistance to both radiotherapy and chemotherapy (113, 114). Recent studies have demonstrated that oxygen deprivation results in decreased expression of pro-apoptotic proteins leading to decreased drug induced apoptosis and clonogenic resistance *in vitro* (115). The tumour microenvironment may therefore have a profound influence on therapeutic outcome, independent of the expression of specific targets in tumour cells. Within this theme, the three dimensional geometry of solid tumours also introduces significant problems related to drug delivery. The poor vascular supply, in conjunction with high interstitial pressures within the tumour, is a recognised barrier to the delivery of therapeutic agents (116, 117). Even if tumour cells express the specific target, there can be no guarantee that sufficient drug will be delivered to cells to elicit a therapeutic response. Whilst significant challenges exist, the use of assays that mimic more closely the heterogeneity within tumours in terms of physiological conditions and drug distribution represent a possible way forward to achieving our goal of individualised therapy.

In conclusion, whilst the modern era of targeted therapeutics offers the potential to tailor therapy to individual patients, past experience with chemotherapeutics such as MMC has demonstrated that prediction of response based on analysis of single target molecules is unlikely to be accurate. Complex mechanisms of action and the effect of the tumour microenvironment on cell biology and drug delivery could thwart attempts to individualise therapies as has been the case with many chemotherapeutic agents. The challenge for the future is to develop assays that mimic key aspects of tumour biology whist retaining the robustness, simplicity and reliability required for routinely predicting tumour response in a clinical setting. Furthermore, incorporating such assays into pre-clinical and early clinical studies would assist in the more rapid development and evaluation of predictive assays.

Acknowledgements

The authors would like to thank S. Basu, R. Puri and the Urological team at Bradford Royal Infirmary and P.M. Loadman (Institute of Cancer Therapeutics) for the provision of superficial bladder cancer specimens and the analysis of mitomycin C metabolism. Thanks also to Professor C. Twelves for valuable discussions and critical review of this manuscript.

References

1 Hamburger AW and Salmon SE: Primary bioassay of human tumor stem cells. Science *197*: 461-463, 1977

2 Nahta R and Esteva FJ: Trastuzumab: mechanisms of action and resistance. Cancer letters *232*: 123-138, 2006.

3 Plosker GL and Keam SJ: Trastuzumab: a review of its use in the management of HER2-positive metastatic and early-stage breast cancer. Drugs *66*: 449-475, 2006.

4 Bartsch R, Wenzel C, Hussian D, Pluschnig U, Sevelda U, Koestler W, Altorjai G, Locker GJ, Mader R, Zielinski CC and Steger GG: Analysis of trastuzumab and chemotherapy in advanced breast cancer after the failure of at least one earlier combination: an observational study. BMC Cancer *6*: 63, 2006.

5 Hata T, Sano Y, Sugawara R, Matsumae A, Kanamerei K, Shima T and Hoshi T: Mitomycin, a new antibiotic from Streptomyces. I J Antibiot Ser *A9*: 141-146, 1956.

6 Sartorelli AC, Hodnick WF, Belcourt MF, Tomasz M, Haffty B, Fischer JJ and Rockwell S: Mitomycin C: a prototype bioreductive agent. Oncol Res *6*: 501-508, 1994.

7 Beretta G: Mitomycin C: clinical updated, 2000.

8 Tolley DA, Parmar MK, Grigor KM, Lallemand G, Benyon LL, Fellows J, Freedman LS, Hall RR, Hargreave TB, Munson K, Newling DW, Richards B *et al*: The effect of intravesical mitomycin C on recurrence of newly diagnosed superficial bladder cancer: a further report with 7 years of follow up. J Urology *155*: 1233-1238, 1996.

9 Bolenz C, Cao Y, Arancibia MF, Trojan L, Alken P and Michel MS: Intravesical mitomycin C for superficial transitional cell carcinoma. Expert Rev Anticancer Ther *6*: 1273-1282, 2006.

10 Basu S, Brown JE, Flannigan GM, Gill JH, Loadman PM, Martin SW, Naylor B, Scally AJ, Seargent JM, Shah TK, Puri R and Phillips RM: Immunohistochemical analysis of NAD(P)H: quinone oxidoreductase and NADPH cytochrome P450 reductase in human superficial bladder tumours: relationship between tumour enzymology and clinical outcome following intravesical mitomycin C therapy. Int J Cancer *109*: 703-709, 2004.

11 Brown JM and Wilson WR: Exploiting tumour hypoxia in cancer treatment. Nature reviews *4*: 437-447, 2004.

12 Kennedy KA, Rockwell S and Sartorelli AC: Preferential activation of mitomycin C to cytotoxic metabolites by hypoxic tumor cells. Cancer Res *40*: 2356-2360, 1980.

13 Workman P: Enzyme-directed bioreductive drug development revisited: a commentary on recent progress and future prospects with emphasis on quinone anticancer agents and quinone metabolizing enzymes, particularly DT-diaphorase. Oncol Res *6*: 461-475, 1994.

14 Workman P and Walton MI: Enzyme directed bioreductive drug development. *In*: Selective Activation of Drugs by Redoc Processesed. Adams GE, Breccia A, Fielden EM, Wardman P (eds.). New York: Plenum Press, pp. 173-191, 1990.

15 Spanswick VJ, Cummings J and Smyth JF: Enzymology of mitomycin C metabolic activation in tumour tissue. Characterization of a novel mitochondrial reductase. Biochem Pharmacol *51*: 1623-1630, 1996.

16 Tomasz M and Palom Y: The mitomycin bioreductive antitumor agents: cross-linking and alkylation of DNA as the molecular basis of their activity. Pharmacol Ther *76*: 73-87, 1997.

17 Cummings J, Spanswick VJ, Tomasz M and Smyth JF: Enzymology of mitomycin C metabolic activation in tumour tisssue. Biochem Pharmacol *56*: 405-414, 1998.

18 Ross D, Beall H, Traver RD, Siegel D, Phillips RM and Gibson NW: Bioactivation of quinones by DT-diaphorase, molecular, biochemical, and chemical studies. Oncol Res *6*: 493-500, 1994.

19 Butler J and Hoey BM: Are reduced quinones necessarily involved in the antitumour activity of quinone drugs? Br J Cancer Suppl *8*: 53-59, 1987.

20 Powis G: Metabolism and reactions of quinoid anticancer agents. Pharmacol Ther *35*: 57-162, 1987.

21 Hoey BM, Butler J and Swallow AJ: Reductive activation of mitomycin C. Biochemistry *27*: 2608-2614, 1988.

22 Palom Y, Suresh Kumar G, Tang LQ, Paz MM, Musser SM, Rockwell S and Tomasz M: Relative toxicities of DNA cross-links and monoadducts: new insights from studies of decarbamoyl mitomycin C and mitomycin C. Chem Res Toxicol *15*: 1398-1406, 2002.

23 Pan SS, Yu F and Hipsher C: Enzymatic and pH modulation of mitomycin C-induced DNA damage in mitomycin C-resistant HCT 116 human colon cancer cells. Mol Pharmacol *43*: 870-877, 1993.

24 Yu F and Pan SS: Effect of pH on DNA alkylation by enzyme-activated mitomycin C and porfiromycin. Mol Pharmacol *43*: 863-869, 1993.

25 Keyes SR, Heimbrook DC, Fracasso PM, Rockwell S, Sligar SG and Sartorelli AC: Chemotherapeutic attack of hypoxic tumor cells by the bioreductive alkylating agent mitomycin C. Adv Enzyme Regul *23*: 291-307, 1985.

26 Plumb JA and Workman P: Unusually marked hypoxic sensitization to indoloquinone EO9 and mitomycin C in a human colon-tumour cell line that lacks DT-diaphorase activity. Int J Cancer *56*: 134-139, 1994.

27 Bligh HF, Bartoszek A, Robson CN, Hickson ID, Kasper CB, Beggs JD and Wolf CR: Activation of mitomycin C by NADPH: cytochrome P-450 reductase. Cancer Res *50*: 7789-7792, 1990.

28 Gustafson DL and Pritsos CA: Bioactivation of mitomycin C by xanthine dehydrogenase from EMT6 mouse mammary carcinoma tumors. J Natl Cancer Inst *84*: 1180-1185, 1992.

29 Komiyama T, Kikuchi T and Sugiura Y: Interactions of anticancer quinone drugs, aclacinomycin A, adriamycin, carbazilquinone, and mitomycin C, with NADPH-cytochrome P-450 reductase, xanthine oxidase and oxygen. J Pharmacobiodyn *9*: 651-664, 1986.

30 Keyes SR, Fracasso PM, Heimbrook DC, Rockwell S, Sligar SG and Sartorelli AC: Role of NADPH: cytochrome c reductase and DT-diaphorase in the biotransformation of mitomycin C1. Cancer Res *44*: 5638-5643, 1984.

31 Jiang HB, Ichikawa M, Furukawa A, Tomita S, Ohnishi T and Ichikawa Y: Metabolic activation of mitomycin C by NADPH-ferredoxin reductase *in vitro*. Life Sci *68*: 1677-1685, 2001.

32 Hodnick WF and Sartorelli AC: Reductive activation of mitomycin C by NADH: cytochrome b5 reductase. Cancer Res *53*: 4907-4912, 1993.

33 Joseph P, Xu Y and Jaiswal AK: Non-enzymatic and enzymatic activation of mitomycin C: identification of a unique cytosolic activity. Int J Cancer *65*: 263-271, 1996.

34 Celli CM and Jaiswal AK: Role of GRP58 in mitomycin C-induced DNA cross-linking. Cancer Res *63*: 6016-6025, 2003.

35 Prieto-Alamo MJ and Laval F: Overexpression of the human HAP1 protein sensitizes cells to the lethal effect of bioreductive drugs. Carcinogenesis *20*: 785-789, 1999.

36 Siegel D, Beall H, Senekowitsch C, Kasai M, Arai H, Gibson NW and Ross D: Bioreductive activation of mitomycin C by DT-diaphorase. Biochemistry *31*: 7879-7885, 1992.

37 Jamieson D, Tung AT, Knox RJ and Boddy AV: Reduction of mitomycin C is catalysed by human recombinant NRH: quinone oxidoreductase 2 using reduced nicotinamide adenine dinucleotide as an electron donating co-factor. Br J Cancer *95*: 1229-1233, 2006.

38 Celli CM, Tran N, Knox R and Jaiswal AK: NRH: quinone oxidoreductase 2 (NQO2) catalyzes metabolic activation of quinones and anti-tumor drugs. Biochem Pharmacol *72*: 366-376, 2006.

39 Ross D, Siegel D, Gibson NW, Pacheco D, Thomas DJ, Reasor M and Wierda D: Activation and deactivation of quinones catalyzed by DT-diaphorase. Evidence for bioreductive activation of diaziquone (AZQ) in human tumor cells and detoxification of benzene metabolites in bone marrow stroma. Free Radic Res Commun *8*: 373-381, 1990.

40 Ernster L: DT Diaphorase: A Historical Review. Chemica Scripta, pp. 1-13, 1987.

41 Ross D, Kepa JK, Winski SL, Beall HD, Anwar A and Siegel D: NAD(P)H: quinone oxidoreductase 1 (NQO1): chemoprotection, bioactivation, gene regulation and genetic polymorphisms. Chem Biol Interact *129*: 77-97, 2000.

42 Phillips RM and Basu S: Biological and clinical significance of polymorphisms in NAD(P)H: Quinone Oxidoreductase 1 (NQO1). Current Pharmacogenomics *2*: 1-8, 2004.

43 Ross D: Quinone reductases multitasking in the metabolic world. Drug Metab Rev *36*: 639-654, 2004.

44 Cadenas E: Antioxidant and prooxidant functions of DT-diaphorase in quinone metabolism. Biochem Pharmacol *49*: 127-140, 1995.

45 Siegel D, Beall H, Kasai M, Arai H, Gibson NW and Ross D: pH-dependent inactivation of DT-diaphorase by mitomycin C and porfiromycin. Mol Pharmacol *44*: 1128-1134, 1993.

46 Siegel D, Gibson NW, Preusch PC and Ross D: Metabolism of mitomycin C by DT-diaphorase: role in mitomycin C-induced DNA damage and cytotoxicity in human colon carcinoma cells. Cancer Res *50*: 7483-7489, 1990.

47 Belinsky M and Jaiswal AK: NAD(P)H: quinone oxidoreductase1 (DT-diaphorase) expression in normal and tumor tissues. Cancer Metastasis Rev *12*: 103-117, 1993.

48 Malkinson AM, Siegel D, Forrest GL, Gazdar AF, Oie HK, Chan DC, Bunn PA, Mabry M, Dykes DJ, Harrison SD *et al*: Elevated DT-diaphorase activity and messenger RNA content in human non-small cell lung carcinoma: relationship to the response of lung tumor xenografts to mitomycin Cl. Cancer Res *52*: 4752-4757, 1992.

49 Siegel D, Franklin WA and Ross D: Immunohistochemical detection of NAD(P)H: quinone oxidoreductase in human lung and lung tumors. Clin Cancer Res *4*: 2065-2070, 1998.

50 Gaedigk A, Tyndale RF, Jurima-Romet M, Sellers EM, Grant DM and Leeder JS: NAD(P)H: quinone oxidoreductase: polymorphisms and allele frequencies in Caucasian, Chinese and Canadian Native Indian and Inuit populations. Pharmacogenetics *8*: 305-313, 1998.

51 Pan SS, Han Y, Farabaugh P and Xia H: Implication of alternative splicing for expression of a variant NAD(P)H: quinone oxidoreductase-1 with a single nucleotide polymorphism at 465C>T. Pharmacogenetics *12*: 479-488, 2002.

52 Traver RD, Horikoshi T, Danenberg KD, Stadlbauer TH, Danenberg PV, Ross D and Gibson NW: NAD(P)H: quinone oxidoreductase gene expression in human colon carcinoma cells: characterization of a mutation which modulates DT6diaphorase activity and mitomycin sensitivity. Cancer Res *52*: 797-802, 1992.

53 Traver RD, Siegel D, Beall HD, Phillips RM, Gibson NW, Franklin WA and Ross D: Characterization of a polymorphism in NAD(P)H: quinone oxidoreductase (DT-diaphorase). Br J Cancer *75*: 69-75, 1997.

54 Schlager JJ and Powis G: Mitomycin C is not metabolized by but is an inhibitor of human kidney NAD(P)H: (quinone-acceptor)oxidoreductase. Cancer Chemother Pharmacol *22*: 126-130, 1988.

55 Vaupel P, Kallinowski F and Okunieff P: Blood flow, oxygen and nutrient supply, and metabolic microenvironment of human tumors: a review. Cancer Res *49*: 6449-6465, 1989.

56 Kozin SV, Shkarin P and Gerweck LE: The cell transmembrane pH gradient in tumors enhances cytotoxicity of specific weak acid chemotherapeutics. Cancer Res *61*: 4740-4743, 2001.

57 Begleiter A, Robotham E, Lacey G and Leith MK: Increased sensitivity of quinone resistant cells to mitomycin C. Cancer Letters *45*: 173-176, 1989.

58 Dulhanty AM and Whitmore GF: Chinese Hamster Ovary cell lines resistant to mitomyinc c under areobic conditions but not hypoxic conditions are deficient in DT-diaphorase. Cancer Res *51*: 1860-1865, 1991.

59 Gibson NW, Hartley JA, Butler J, Siegel D and Ross D: Relationship between DT-diaphorase-mediated metabolism of a series of aziridinylbenzoquinones and DNA damage and cytotoxicity. Mol Pharmacol *42*: 531-536, 1992.

60 Siegel D, Gibson NW, Preusch PC and Ross D: Metabolism of diaziquone by NAD(P)H: (quinone acceptor) oxidoreductase (DT-diaphorase): role in diaziquone-induced DNA damage and cytotoxicity in human colon carcinoma cells. Cancer Res *50*: 7293-7300, 1990.

61 Fitzsimmons SA, Workman P, Grever M, Paull K, Camalier R and Lewis AD: Reductase enzyme expression across the National Cancer Institute Tumor cell line panel: correlation with sensitivity to mitomycin C and EO9. J Natl Cancer Inst *88*: 259-269, 1996.

62 Robertson N, Stratford IJ, Houlbrook S, Carmichael J and Adams GE: The sensitivity of human tumour cells to quinone bioreductive drugs: what role for DT-diaphorase? Biochem Pharmacol *44*: 409-412, 1992.

63 Choudry GA, Hamilton Stewart PA, Double JA, Krul MRL, Naylor B, Flannigan GM, Shah TK, Brown JE and Phillips RM: A novel styrategy for NQO1 (NAD(P)H: quinone oxidoreductase, EC1.6.99.2) mediated therapy of bladder cancer based on the pharmacologocal properties of EO9. Br J Cancer *85*: 1137-1146, 2001.

64 Phillips RM, Burger AM, Loadman PM, Jarrett CM, Swaine DJ and Fiebig HH: Predicting tumor responses to mitomycin C on the basis of DT-diaphorase activity or drug metabolism by tumor homogenates: implications for enzyme-directed bioreductive drug development. Cancer Res *60*: 6384-6390, 2000.

65 Hodnick WF and Sartorelli AC: Measurement of dicumarol-sensitive NADPH: (menadione-cytochrome c) oxidoreductase activity results in an artifactual assay of DT-diaphorase in cell sonicates. Anal Biochem *252*: 165-168, 1997.

66 Belcourt MF, Hodnick WF, Rockwell S and Sartorelli AC: Bioactivation of mitomycin antibiotics by aerobic and hypoxic Chinese hamster ovary cells overexpressing DT-diaphorase. Biochem Pharmacol *51*: 1669-1678, 1996.

67 Sharp SY, Kelland LR, Valenti MR, Brunton LA, Hobbs S and Workman P: Establishment of an isogenic human colon tumor model for NQO1 gene expression: application to investigate the role of DT-diaphorase in bioreductive drug activation *in vitro* and *in vivo*. Mol Pharmacol *58*: 1146-1155, 2000.

68 Winski SL, Swann E, Hargreaves RH, Dehn DL, Butler J, Moody CJ and Ross D: Relationship between NAD(P)H: quinone oxidoreductase 1 (NQO1) levels in a series of stably transfected cell lines and susceptibility to antitumor quinones. Biochem Pharmacol *61*: 1509-1516, 2001.

69 Gustafson DL, Beall HD, Bolton EM, Ross D and Waldren CA: Expression of human NAD(P)H: quinone oxidoreductase (DT-diaphorase) in Chinese hamster ovary cells: effect on the toxicity of antitumor quinones. Mol Pharmacol *50*: 728-735, 1996.

70 Powis G, Gasdaska PY, Gallegos A, Sherrill K and Goodman D: Over-expression of DT-diaphorase in transfected NIH 3T3 cells does not lead to increased anticancer quinone drug sensitivity: a questionable role for the enzyme as a target for bioreductively activated anticancer drugs. Anticancer Res *15*: 1141-1145, 1995.

71 Marshall RS, Paterson MC and Rauth AM: DT-diaphorase activity and mitomycin C sensitivity in non-transformed cell strains derived from members of a cancer-prone family. Carcinogenesis *12*: 1175-1180, 1991.

72 O'Dwyer PJ, Perez RP, Yao KS, Godwin AK and Hamilton TC: Increased DT-diaphorase expression and cross-resistance to mitomycin C in a series of cisplatin-resistant human ovarian cancer cell lines. Biochemical pharmacology *52*: 21-27, 1996.

73 Keyes SR, Rockwell S and Sartorelli AC: Enhancement of mitomycin C cytotoxicity to hypoxic tumor cells by dicoumarol *in vivo* and *in vitro*. Cancer Res *45*: 213-216, 1985.

74 Gustafson DL and Pritsos CA: Enhancement of xanthine dehydrogenase mediated mitomycin C metabolism by dicumarol. Cancer Res *52*: 6936-6939, 1992.

75 Begleiter A, Leith MK and Curphey TJ: Induction of DT-diaphorase by 1,2-dithiole-3-thione and increase of antitumour activity of bioreductive agents. Br J Cancer Suppl *27*: S9-14, 1996.

76 Begleiter A, Leith MK, Thliveris JA and Digby T: Dietary induction of NQO1 increases the antitumour activity of mitomycin C in human colon tumours *in vivo*. Br J Cancer *91*: 1624-1631, 2004.

77 Lin YL, Ho IC, Su PF and Lee TC: Arsenite pretreatment enhances the cytotoxicity of mitomycin C in human cancer cell lines *via* increased NAD(P)H quinone oxidoreductase 1 expression. Toxicol Appl Pharmacol *214*: 309-317, 2006.

78 Ross D, Siegel D, Beall H, Prakash AS, Mulcahy RT and Gibson NW: DT-diaphorase in activation and detoxification of quinones. Bioreductive activation of mitomycin C. Cancer Metastasis Rev *12*: 83-101, 1993.

79 Anwar A, Dehn D, Siegel D, Kepa JK, Tang LJ, Pietenpol JA and Ross D: Interaction of human NAD(P)H: quinone oxidoreductase 1 (NQO1) with the tumor suppressor protein p53 in cells and cell-free systems. J Biol Chem *278*: 10368-10373, 2003.

80 Asher G, Lotem J, Cohen B, Sachs L and Shaul Y: Regulation of p53 stability and p53-dependent apoptosis by NADH quinone oxidoreductase 1. Proc Natl Acad Sci USA *98*: 1188-1193, 2001.

81 Plumb JA, Gerritsen M, Milroy R, Thomson P and Workman P: Relative importance of DT-diaphorase and hypoxia in the bioactivation of EO9 by human lung tumor cell lines. Int J Radiat Oncol Biol Phys *29*: 295-299, 1994.

82 Keyes SR, Loomis R, DiGiovanna MP, Pritsos CA, Rockwell S and Sartorelli AC: Cytotoxicity and DNA crosslinks produced by mitomycin analogs in aerobic and hypoxic EMT6 cells. Cancer Commun *3*: 351-356, 1991.

83 Traver RD, Horikoshi T, Danenberg KD, Stadlbauer TH, Danenberg PV, Ross D and Gibson NW: NAD(P)H: quinone oxidoreductase gene expression in human colon carcinoma cells: characterization of a mutation which modulates DT6diaphorase activity and mitomycin sensitivity. Cancer Res *52*: 797-802, 1992.

84 Hu LT, Stamberg J and Pan S: The NAD(P)H: quinone oxidoreductase locus in human colon carcinoma HCT 116 cells resistant to mitomycin C. Cancer Res *56*: 5253-5259, 1996.

85 Pan SS, Forrest GL, Akman SA and Hu LT: NAD(P)H: quinone oxidoreductase expression and mitomycin C resistance developed by human colon cancer HCT 116 cells. Cancer Res *55*: 330-335, 1995.

86 Yano M, Akiyama Y, Shiozaki H, Inoui Y, Doki Y, Fujiwara D, Ross D, Sadler A and Monden M: Genetic polymorphism of NAD(P)H: quinone oxidoreductase and mitomycin C sensitivity in gastric cancer. American Assocciation for Cancer Res *41*: 4-5, 2000.

87 Nishiyama M, Suzuki K, Kumazaki T, Yamamoto W, Toge T, Okaruma T and Kurisu K: Molecular targeting of mitomycin C chemotherapy. Int J Cancer *72*: 649-656, 1997.

88 Pritsos CA, Pardini LL, Elliott AJ and Pardini RS: Relationship between the antioxidant enzyme DT-diaphorase and tumor response to mitomycin C treatment. Basic Life Sci *49*: 713-716, 1988.

89 Nishiyama M, Saeki S, Aogi K, Hirabayashi N and Toge T: Relevance of DT-diaphorase activity to mitomycin C (MMC) efficacy on human cancer cells: differences in *in vitro* and *in vivo* systems. Int J Cancer *53*: 1013-1016, 1993.

90 Gan Y, Mo Y, Kalns JE, Lu J, Danenberg K, Danenberg P, Wientjes MG and Au JL: Expression of DT-diaphorase and cytochrome P450 reductase correlates with mitomycin C activity in human bladder tumors. Clin Cancer Res *7*: 1313-1319, 2001.

91 Basu S, Brown JE, Flannigan GM, Gill JH, Loadman PM, Martin SW, Naylor B, Scally AJ, Seargent JM, Shah TK, Puri R and Phillips RM: Immunohistochemical analysis of NAD(P)H: quinone oxidoreductase and NADPH cytochrome P450 reductase in human superficial bladder tumours: relationship between tumour enzymology and clinical outcome following intravesical mitomycin C therapy. Internat J Cancer *109*: 703-709, 2004.

92 Fleming RA, Drees J, Loggie BW, Russell GB, Geisinger KR, Morris RT, Sachs D and McQuellon RP: Clinical significance of a NAD(P)H: quinone oxidoreductase 1 polymorphism in patients with disseminated peritoneal cancer receiving intraperitoneal hyperthermic chemotherapy with mitomycin C. Pharmacogenetics *12*: 31-37, 2002.

93 Phillips RM, Burger AM, Fiebig HH and Double JA: Genotyping of NAD(P)H: quinone oxidoreductase (NQO1) in a panel of human tumor xenografts: relationship between genotype status, NQO1 activity and the response of xenografts to Mitomycin C chemotherapy *in vivo*. Biochem Pharmacol *62*: 1371-1377, 2001.

94 Basu S, Brown JE, Flannigan GM, Gill JH, Loadman PM, Martin SW, Naylor B, Scally AJ, Seargent JM, Shah TK, Puri R and Phillips RM: NAD(P)H: quinone oxidoreductase -1 C609T polymorphism analysis in human superficial bladder cancers: relationship of genotype status to NQO1 phenotype and clinical resposne to mitomycin C. Int J Oncol *25*: 921-927, 2004.

95 Ishida T, Nishio K, Kurokawa H, Arioka H, Fukumoto H, Fukuoka K, Nomoto T, Yokote H, Hasegawa S and Saijo N: Circumvention of glutathione-mediated mitomycin C resistance by a novel mitomycin C analogue, KW-2149. Int J Cancer *72*: 865-870, 1997.

96 Volpato M, Seargent J, Loadman PM and Phillips RM: Formation of DNA interstrand cross-links as a marker of Mitomycin C bioreductive activation and chemosensitivity. Eur J Cancer *41*: 1331-1338, 2005.

97 De Silva IU, McHugh PJ, Clingen PH and Hartley JA: Defining the roles of nucleotide excision repair and recombination in the repair of DNA interstrand cross-links in mammalian cells. Molecular and cellular biology *20*: 7980-7990, 2000.

98 Sancar A and Reardon JT: Nucleotide excision repair in *E. coli* and man. Adv Protein Chem *69*: 43-71, 2004.

99 McKeown SR, Robson T, Price ME, Ho ETS, Hirst DG and McKelvey-Martin VJ: Potential use of the alkaline comet assay as a predictor of bladder tumour response to radiation. Brit J Cancer *89*: 2264-2270, 2003.

100 Moneef MAL, Sherwood BT, Bowman KJ, Kockelbergh RC, Symonds RP, Steward WP, Mellon JK and Jones GDD: Measurements using the alkaline comet assay predict bladder cancer cell radiosensitivity. Br J Cancer *89*: 2271-2276, 2003.

101 El-Awady RA, Dikomey E and Dahm-Daphi J: Radiosensitivity of human tumour cells is correlated with the induction but not with the repair of DNA double-strand breaks. Br J Cancer *89*: 593-601, 2003.

102 Mueller S, Holdenrieder S, Stieber P, Haferlach T, Schalhorn A, Braess J, Nagel D and Seidel D: Early prediction of therapy response in patients with acute myeloid leukemia by nucleosomal DNA fragments. BMC Cancer *6*: 143, 2006.

103 Kelly JD, Williamson KE, Weir HP, McManus DT, Hamilton PW, Keane PF and Johnston SR: Induction of apoptosis by mitomycin-C in an *ex vivo* model of bladder cancer. BJU Int *85*: 911-917, 2000.

104 Sun X and Ross D: Quinone-induced apoptosis in human colon adenocarcinoma cells *via* DT-diaphorase mediated bioactivation. Chemico-Biological Interactions *100*: 267-276, 1996.

105 Gontero P, Sargent JM, Hopster DJ, Lewandowic GM, Taylor CG, Elgie AW, Williamson CJ, Sriprasad SI and Muir GH: *Ex vivo* chemosensitivity to mitomycin c in bladder cancer and its relationship with P-glycoprotein and apoptotic factors. Anticancer Res *22*: 4073-4080, 2002.

106 Hsueh C-T, Chiu C-F, Kelsen DP and Schwartz GK: Selective inhibition of cyclooxygenase-2 enhances mitomycin C induced apoptosis. Cancer Chemother Pharmacol *45*: 389-396, 2000.

107 Schwartz GK, Haimovitz-Friedman A, Dhupar SK, Ehleiter D, Maslak P, Lai L, Loganzo JF, Kelsen DP, Fuks Z and Albino AP: Potentiation of apoptosis by treatment with the protein kinase C-specific inhibitor Safingol in mitomycin C treated gastric cancer cells. J Natl Cancer Inst *87*: 1394-1399, 1995.

108 Shang X, Shiono Y, Fujita Y, Oka S and Yamazaki Y: Synergistic enhancement of apoptosis by DNA- and cytoskeleton-damaging agents: a basis for combination chemotherapy of cancer. Anticancer Res *21*: 2585-2590, 2001.

109 Okada H and Mak TW: Pathways of apoptotic and non-apoptotic death in tumour cells. Nature Cancer Reviews *4*: 592-603, 2004.

110 Pirnia F, Frese S, Gloor B, Hotz MA, Luethi A, Gugger M, Betticher DC and Borner MM: *Ex vivo* assessment of chemotherapy-induced apoptosis and associated molecular changes in patient tumor samples. Anticancer Res *26*: 1765-1772, 2006.

111 Dunne AL, Price ME, Mothersill C, McKeown SR, Robson T and Hirst DG: Relationship between clonogenic radiosensitivity, radiation-induced apoptosis and DNA damage/repair in human colon cancer cells. Br J Cancer *89*: 2277-2283, 2003.

112 Kubota T: Gastrointestinal stromal tumor (GIST) and imatinib. Internat J Clinic Oncol / Japan Society Clinic Oncol *11*: 184-189, 2006.

113 Vaupel P: Tumor microenvironmental physiology and its implications for radiation oncology. Semin Radiat Oncol *14*: 198-206, 2004.

114 Vaupel P and Hockel M: Blood supply, oxygenation status and metabolic micromilieu of breast cancers: characterization and therapeutic relevance. Int J Oncol *17*: 869-879, 2000.

115 Erler JT, Cawthorne CJ, Williams KJ, Koritzinsky M, Wouters BG, Wilson C, Miller C, Demonacos C, Stratford IJ and Dive C: Hypoxia-mediated down-regulation of Bid and Bax in tumors occurs *via* hypoxia-inducible factor 1-dependent and -independent mechanisms and contributes to drug resistance. Mol Cell Biol *24*: 2875-2889, 2004.

116 Fukumura D and Jain RK: Tumor microenvironment abnormalities: Causes, consequences, and strategies to normalize. J Cell Biochem, 2007 [Ahead of publication].

117 Minchinton AI and Tannock IF: Drug penetration in solid tumours. Nature reviews *6*: 583-592, 2006.

118 Doroshow JH, Akman S, Chu FF and Esworthy S: Role of the glutathione-glutathione peroxidase cycle in the cytotoxicity of the anticancer quinones. Pharmacol Ther *47*: 359-370, 1990.

Received February 13, 2007
Accepted February 20, 2007