Hypersensitivity of Skin Fibroblasts from Basal Cell Nevus Syndrome Patients to Killing by Ultraviolet B but not by Ultraviolet C Radiation

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ABSTRACT

Basal cell nevus syndrome (BCNS) is an autosomal dominant genetic disorder in which the afflicted individuals are extremely susceptible to sunlight-induced skin cancers, particularly basal cell carcinomas. However, the cellular and molecular basis for BCNS is unknown. To ascertain whether there is any relationship between genetic predisposition to skin cancer and increased sensitivity of somatic cells from BCNS patients to killing by UV radiation, we exposed skin fibroblasts established from unexposed skin biopsies of several BCNS and age- and sex-matched normal individuals to either UV-B (280–320 nm) or UV-C (254 nm) radiation and determined their survival. The results indicated that skin fibroblasts from BCNS patients were hypersensitive to killing by UV-B but not by UV-C radiation as compared to skin fibroblasts from normal individuals. DNA repair studies indicated that the increased sensitivity of BCNS skin fibroblasts to killing by UV-B radiation was not due to a defect in the excision repair of pyrimidine dimers. These results indicate that there is an association between hypersensitivity of somatic cells to killing by UV-B radiation and the genetic predisposition to skin cancer in BCNS patients. In addition, these results suggest that DNA lesions (and repair processes) other than the pyrimidine dimer are also involved in the pathogenesis of sunlight-induced skin cancers in BCNS patients. More important, the UV-B sensitivity assay described here may be used as a diagnostic tool to identify presymptomatic individuals with BCNS.

INTRODUCTION

BCNS,3 also known as nevoid basal cell carcinoma syndrome or Gorlin’s syndrome, is an autosomal dominant disorder with high penetrance (>97%) (1-4). The principal manifestations of this syndrome are multiple BCC, palmar and plantar pitting, and systemic (jaw cysts) and musculoskeletal abnormalities (scoliosis, bifurcated rib, spina bifida) (5-9). This high incidence of developmental anomalies suggests that the normal allele of the BCNS gene may play a role in growth and development. While BCC in normal individuals are generally solitary, occur on sun-exposed body sites, and do not usually appear until later in life, the nevoid BCC occur as multiple tumors (average, 50–100), primarily on sun-exposed skin, and usually appear at puberty and during the second and third decade of life. These observations suggest that the process of carcinogenesis is accelerated in BCNS. However, the cellular and molecular basis for BCNS is unknown.

That individuals with BCNS also develop other neoplasms such as medulloblastoma and ovarian and uterine fibromas (5-11) has led to the hypothesis that BCNS fits Knudson’s two-mutation model for carcinogenesis (12, 13). However, the number of such mutations required to induce cancers in BCNS individuals is unknown and could be higher than two. Nevertheless, in BCNS, one of the mutations is inherited as an autosomal dominant gene in all somatic cells, whereas the remaining mutation(s) is induced by radiation. This hypothesis is supported by the observation that presymptomatic BCNS children treated with radiation for medulloblastoma developed multiple BCC in the area that received radiation 6 months to 3 years after treatment (14). Radiosensitivity studies using fibroblasts from BCNS individuals have, however, led to contradictory results. While most studies have failed to show any unusual sensitivity of BCNS fibroblasts to cell killing by X-rays, γ-rays, α-particles, or mitomycin C (15-18), Chan and Little (19) reported that BCNS fibroblasts were hypersensitive to killing by ionizing radiation. On the other hand, Little et al. (20) did not find any consistent pattern of increased sensitivity of BCNS cells to killing by X-irradiation. The ability of BCNS fibroblasts to repair X-ray-induced DNA damage was also normal (18, 19). In contrast, Arlett and Priestley (21) have reported that cells from BCNS patients were defective in the repair of γ-ray-induced potentially lethal damage. Thus more studies are needed to resolve this controversy.

Attempts to demonstrate an increased sensitivity of somatic BCNS cells to killing by UV radiation have been unsuccessful. Studies by Little et al. (20) and Lehmann et al. (22) have shown that fibroblasts from BCNS patients exhibit normal survival following UV irradiation. However, Nagasawa et al. (23) have reported that BCNS fibroblasts were slightly more sensitive to UV radiation than normal fibroblasts. In any case, these studies were conducted using UV-C radiation (254 nm), a wavelength that is filtered out by the stratospheric ozone. Since epidemiological and clinical studies indicate that UV-B radiation (280–320 nm), which reaches the surface of the earth in sunlight, is responsible for the induction of most skin cancers in humans (24, 25), it is important to use these wavelengths in sensitivity studies on human cells, particularly from individuals genetically predisposed to sunlight-induced skin cancers. When we determined the sensitivity of skin fibroblasts from BCNS and age- and sex-matched normal individuals to killing by UV-B radiation, we found that skin fibroblasts from BCNS individuals were hypersensitive compared with the skin fibroblasts from age- and sex-matched normal individuals.

MATERIALS AND METHODS

Cell Cultures. None of the BCNS patients had undergone radiotherapy or chemotherapy for BCC at the time of skin biopsy. Three normal male (ages 32, 33, and 43 years) and two female (ages 33 and 50 years) volunteers, all Caucasians, were chosen as controls. Skin tissues (>6 mm in diameter) from non-sun-exposed areas from 5 BCNS patients and 5 normal individuals were surgically excised, cut into small fragments (<0.5 mm3), transferred to T-25 tissue culture flasks (Falcon), and grown in DMEM (GIBCO) containing 20% calf serum (HyClone), penicillin (100 units/ml), and streptomycin (100 μg/ml) at 37°C in a humidified atmosphere of 95% air/5% CO2. The culture medium was renewed twice weekly. After 2–3 weeks, primary fibroblasts were treated...
with 0.25% trypsin-0.1% EDTA and grown initially in T-75 flasks and later in T-150 flasks. When sufficient number of cells were reached, they were frozen in liquid N₂ in 1-ml aliquots containing ~5 × 10⁵ cells/ml. As needed, frozen cells were thawed quickly and grown in T-150 flasks in DMEM for 2-3 days before using in experiments.

Light Sources. A short-wavelength germicidal lamp (Ultra-violet Products, Inc., San Gabriel, CA) was used as a source of UVC radiation. This light source emits primarily 254 nm radiation. An unfiltered FS40T12 sunlamp (National Biological Corporation, Twinsburg, OH) was used as a source of UV-B radiation. The unfiltered FS40 sunlamp emits wavelengths predominately between 280 and 400 nm (99.4% of the total UV radiation) with a peak emission at 314 nm. The fluorescence rates of the FS40 sunlamp and the germicidal lamp at a source to target distance of 20 cm (from the light bulb to the bottom of the tissue culture dish) were 4.4 and 1 W/m², respectively. The fluorescence was measured by a calibrated Optronics model 742 spectroradiometer (Optronics Laboratories, Orlando, FL). The scanning radiometer measures the spectral emissions at 1-nm intervals and integrates the emitted energies.

UV Survival Assays. Cells (750/dish) were plated in 60-mm tissue culture dishes in complete DMEM. About 6 h after plating, the medium was removed and the cells were washed once with 2 ml of PBS and then irradiated at room temperature in 1 ml of PBS with the dish cover off using an unfiltered FS40T12 sunlamp or a germicidal lamp. A set of unirradiated cultures was treated similarly, except that they were kept in the dark for the duration of the irradiation period. After irradiation, PBS was removed, medium was added, and the plates were incubated at 37°C. After 7–10 days of growth, the dishes were stained with methylene blue and the colonies were counted using a dissecting microscope. The colony forming efficiency of untreated BCNS and normal human skin fibroblasts was 20-25%. All operations were carried out with the laminar flow hood and overhead room fluorescent lights off.

Pyrimidine Dimer and Excision Repair Assays. Exponentially growing cells (5 × 10⁵/dish) were grown in complete DMEM containing 0.5 µCi/ml of [³H]thymidine (specific activity, 20 Ci/mmol). After overnight incubation at 37°C, the medium was replaced with fresh nonradioactive DMEM and incubated for 1 h. The cells were washed with PBS and exposed to 100 J/m² of UV-B radiation from a FS40T12 sunlamp, as described above. The numbers of pyrimidine dimers present in the DNA of UV-B-irradiated BCNSs and normal human skin fibroblasts were measured either immediately after UV irradiation or after 6 or 12 h of post-UV recovery using the damage-specific endonucleases from Micrococcus luteus, as described before (26). Damage-specific endonucleases were partially purified from M. luteus by the method of Carrier and Setlow (27). Briefly, crude extracts of spray-dried cells (Miles Chemical Co., Elkhart, IN) were precipitated with ammonium sulfate (final concentrations, 65%) and then fractionated on a DE52 cellulose column. The resulting eluate, referred to as fraction III (27), represented about 6-fold purification and contained most of the endonuclease activity. This fraction was used in ESS assays.

ESS (pyrimidine dimers) were determined by incubating 200 µl (~2000 cpm) of DNA with 20 µl of "assay mix" (50 mM EDTA, 100 µg crude yeast tRNA/ml, and 200 µg sonicated calf thymus DNA/ml in 50 mM phosphate buffer, pH 7.0) and 20 µl of M. luteus extract for 30 min at 37°C. The reaction was stopped by the addition of 100 µl of 1 N NaOH. The incubation was continued for another 30 min to assure complete denaturation of the DNA; layered onto a 4.6-ml alkaline 5-15% sucrose gradient containing 0.7 M NaCl, 0.3 M NaOH, and 0.01 M EDTA; and centrifuged in a Beckman SW50.1 rotor at 30,000 rpm for 180 min. The distribution of radioactivity in the gradients was determined by the paper strip method of Carrier and Setlow (28). Number-average molecular weights (Mₐ) were calculated from the weight-average molecular weights since direct calculation of Mₑ is very sensitive to small fluctuations in the low molecular weight region of the gradients. The number of ESS per 10⁸ daltons of DNA was calculated as:

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\text{No. of ESS/10}^8 \text{ daltons DNA} = 10^8 \left( \frac{1}{M_a} - \frac{1}{M_e} \right)
\]

where Mₑ and Mₐ are the Mₚs of the DNA observed with and without treatment with M. luteus enzyme, respectively.

RESULTS

We have assembled a group of pedigrees in which the BCNS is inherited as an autosomal dominant trait. On the basis of clinical observations and personal interviews with the patients and their family members, we were able to follow the occurrence of BCNS in 3 families from Houston and 1 from Galveston, representing 3–4 generations. As can be seen in Fig. 1, the mode of inheritance of the BCNS gene in these families appears to be dominant with multiple and variable expression, so that affected children have an affected parent, and there is no sex predilection. All the patients participating in this study had multiple BCC (100+). The case histories of the 5 adult BCNS patients participating in this study are shown in Table 1. In addition to multiple BCC, all the patients also exhibited one or more of the other abnormalities (such as palmar pits, jaw cysts, scoliosis, etc.) that are commonly associated with BCNS. Patients 1, 2, and 3 had palmar pits (since age ~15 years), jaw cysts, mild scoliosis, pectus excavatus, and milia. Although patients 4 and 5 had palmar pits, it is not certain at what age this symptom manifested. In addition, no clear information is available to indicate whether patients 4 and 5 have jaw cysts or musculoskeletal abnormalities.

Fibroblast cell strains established from biopsy samples of the non-sun-exposed skin of 5 BCNS patients and 5 normal age-
and sex-matched individuals were exposed to UV-B radiation from an FS40 sunlamp. The UV-B survival curves for BCNS and normal human skin fibroblasts are shown in Fig. 2. Skin fibroblasts from all 5 BCNS patients were hypersensitive to killing by UV-B radiation compared to the fibroblasts from age- and sex-matched normal individuals. In addition, the BCNS skin fibroblasts did not exhibit a shoulder, whereas the normal human skin fibroblasts exhibited a broad shoulder, which are suggestive of single-hit and multiple-hit kinetics, respectively. The dose required to reduce survival by 50% for BCNS fibroblasts was ~25 J/m², whereas for normal human skin fibroblasts, it was ~150 J/m², about 6-fold increase in sensitivity. However, at doses of >50 J/m², BCNS skin fibroblasts were about 3-fold more sensitive to killing by UV-B than normal human skin fibroblasts. This difference stemmed largely from the biphasic nature of the curve for BCNS patients which exhibited a steep decline in survival initially followed by a relatively more resistant component. The latter component appeared to be running more or less parallel to that of the normal human skin fibroblast survival curve.

We next performed survival experiments using a germicidal lamp to determine whether skin fibroblasts from BCNS patients were also hypersensitive to UV-C radiation. The results shown in Fig. 3 indicate that the sensitivity of BCNS skin fibroblasts to killing by UV-C radiation was similar to that of normal human skin fibroblasts. UV radiation induces primarily cyclobutane-type pyrimidine dimers in the DNA (29). In order to ascertain whether the increased sensitivity of BCNS skin fibroblasts to killing by UV-B radiation was due to a defect in the excision repair of UV-B-induced pyrimidine dimers, we measured the number of pyrimidine dimers remaining in cellular DNA at 6 or 24 h post-UV-B. These time points were chosen because it has been reported that human cells exhibit a biphasic excision repair kinetics where ~50% of the pyrimidine dimers are repaired in the first few hours and the remaining are repaired by 24 h (30, 31). The results shown in Fig. 4 reveal that the percent of induced pyrimidine dimers remaining at 6 or 24 h of post-UV-B recovery was similar in both BCNS and normal human skin fibroblasts. The rate of excision repair of pyrimidine dimers in BCNS and normal human skin fibroblasts was 40–50% at 6 h and 70–80% at 24 h. This indicates that the excision repair of UV-B-induced pyrimidine dimers is very efficient in both BCNS and normal human skin fibroblasts.

**DISCUSSION**

The results presented here demonstrate that early passage fibroblasts established from unexposed skin biopsies of BCNS patients were hypersensitive to killing by UV-B radiation as compared with the skin fibroblasts from age- and sex-matched normal individuals. The skin fibroblasts from BCNS patients were 3- to 6-fold more sensitive, depending upon the survival point at which the sensitivity factor was calculated, to the cytotoxic effects of UV-B than the skin fibroblasts from normal individuals. Furthermore, the BCNS skin fibroblasts exhibited a biphasic survival curve in which there was a sharp decline in survival in the early portion of the survival curve. These results suggest that an unusually sensitive subpopulation of cells may exist in cultures derived from BCNS patients. In contrast to the increased sensitivity of BCNS skin fibroblasts to killing by UV-B radiation, their sensitivity to killing by UV-C radiation was similar to that of normal human skin fibroblasts. These results are in agreement with those of Little et al. (20) and Lehmann et al. (22) who also found that skin fibroblasts from BCNS patients exhibited normal survival following UV-C irradiation. However, Nagasawa et al. (23) have reported that BCNS fibroblasts were slightly more sensitive to UV-C radiation than normal fibroblasts.

The increased sensitivity of BCNS skin fibroblasts to killing by UV-B radiation cannot be attributed to a defect in the repair
of cyclobutane-type pyrimidine dimers because the excision repair kinetics of UV-B-induced pyrimidine dimers in BCNS skin fibroblasts was similar to that of normal human skin fibroblasts. Once again, these results are in agreement with those of Lehmann et al. (22), who found that BCNS fibroblasts irradiated with UV-C radiation exhibited normal levels of dimer excision and postreplication repair. However, Nagasawa et al. (23) and Ringborg et al. (32) reported that BCNS cells may have a reduced capacity for the repair of some type of UV-induced DNA damage, as determined by unscheduled DNA synthesis. Our results suggest that BCNS cells may have a defect in the repair of some other, as yet unidentified, UV-B-induced photoproduct. Alternatively, the increased sensitivity of BCNS skin fibroblasts to killing by UV-B irradiation could be due to reduced repair of specific gene lesions. Recent studies have shown that fibroblasts from Cockayne’s syndrome patients exhibit normal repair of genomic DNA lesions but are deficient in the repair of specific DNA lesions in actively transcribing regions of DNA (33). In addition, Bohr et al. (34) found that efficient removal of pyrimidine dimers in the dihydrofolate reductase gene in Chinese hamster ovary cells correlated with survival, indicating that repair in essential genes is perhaps the ultimate criterion for cell survival following UV irradiation. Analogous to BCNS, individuals with the genetic disorder XP are also predisposed to sunlight-induced skin cancers. However, our studies indicate that skin fibroblasts from BCNS patients exhibit unique characteristics that are quite different from skin fibroblasts from XP patients. While XP skin fibroblasts are hypersensitive to killing by UV-C irradiation (35, 36) and are defective in excision repair of UV-induced pyrimidine dimers (37, 38), BCNS skin fibroblasts exhibit similar UV-C survival and excision repair of pyrimidine dimers as normal human skin fibroblasts. This suggests that the molecular lesions responsible for cell killing and induction of skin cancers in XP and BCNS patients may be different. If this is true, then somatic cells from BCNS patients may be of value as a new model system for studying the molecular mechanisms of UV carcinogenesis. Recent studies indicate that UV radiation also induces non-dimer photochemical products such as (6-4) photoproducts (39–41), cytosine photohydrates (42–44), purine photoproducts (45), and single-strand breaks in the DNA (46–48). Various data suggest that (6-4) photoproducts may play a role in UV-induced lethality and mutagenesis (49–51). Interestingly, Cleaver et al. (52) found that a revertant XP cell line obtained by ethyl methanesulfonate mutagenesis of XP12RO cell line exhibited differential repair of pyrimidine dimers and (6-4) photoproducts. While the parent XP cell line failed to repair both these photochemicals, the revertant XP cell line was able to repair (6-4) photoproducts but not pyrimidine dimers. These results suggest that in human cells (6-4) photoproducts may play a more important role in UV-induced lethality and mutagenesis than pyrimidine dimers. On the other hand, it is also possible that generation of Dewar bases from (6-4) photoproducts, a process that is preferentially catalyzed by UV-B radiation (53–57), may be involved in the UV-B hypersensitivity of BCNS skin fibroblasts. It is reported that cytosine photohydrates and purine photoproducts, while sparedly formed by UV-C irradiation, are maximally formed by UV-B irradiation (42–45). Therefore, these two photochemicals may also be involved in the hypersensitivity of BCNS skin fibroblasts to killing by UV-B radiation. It remains to be determined whether deficient repair of any of these non-dimer photochemicals is involved in the preferential killing of BCNS cells by UV-B radiation.

In summary, our studies indicate that there is an association between hypersensitivity of somatic cells to killing by UV-B radiation and the genetic predisposition to BCC in BCNS patients. In addition, our results suggest that DNA lesions (and repair processes) other than the pyrimidine dimer may also be involved in the pathogenesis of sunlight-induced BCC in BCNS patients. More important, we may be able to use the UV-B sensitivity assay as a diagnostic tool to identify presymptomatic children and adults of BCNS-affected families who are predisposed to cancer. Lastly, since the FS40 sunlamp used in these studies also emit substantial wavelengths in the UV-A (320–400 nm) region, it is possible that the skin fibroblasts from BCNS patients may also be hypersensitive to killing by UV-A radiation. This is currently under investigation.

ACKNOWLEDGMENTS

The authors wish to thank Dr. Margaret Kripke for comments on the manuscript.

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