

Asymptotic Properties of Self-Consistent Estimators Based on Doubly Censored Data



M. G. Gu; C.-H. Zhang

The Annals of Statistics, Vol. 21, No. 2. (Jun., 1993), pp. 611-624.

Stable URL:

<http://links.jstor.org/sici?sici=0090-5364%28199306%2921%3A2%3C611%3AAPOSEB%3E2.0.CO%3B2-R>

The Annals of Statistics is currently published by Institute of Mathematical Statistics.

Your use of the JSTOR archive indicates your acceptance of JSTOR's Terms and Conditions of Use, available at <http://www.jstor.org/about/terms.html>. JSTOR's Terms and Conditions of Use provides, in part, that unless you have obtained prior permission, you may not download an entire issue of a journal or multiple copies of articles, and you may use content in the JSTOR archive only for your personal, non-commercial use.

Please contact the publisher regarding any further use of this work. Publisher contact information may be obtained at <http://www.jstor.org/journals/ims.html>.

Each copy of any part of a JSTOR transmission must contain the same copyright notice that appears on the screen or printed page of such transmission.

JSTOR is an independent not-for-profit organization dedicated to creating and preserving a digital archive of scholarly journals. For more information regarding JSTOR, please contact support@jstor.org.

ASYMPTOTIC PROPERTIES OF SELF-CONSISTENT ESTIMATORS BASED ON DOUBLY CENSORED DATA

BY M. G. GU¹ AND C.-H. ZHANG²

McGill University and Rutgers University

This paper concerns self-consistent estimators for survival functions based on doubly censored data. We establish strong uniform consistency, asymptotic normality and asymptotic efficiency of the estimators under mild conditions on the distributions of the censoring variables.

1. Introduction. In biometry and reliability studies, the distribution function of the underlying lifetime is often of special interest. It is common in these problems that the observations are incomplete, therefore the empirical distribution function is not appropriate in estimating the distribution function of the lifetime. In the right-censoring case the product limit estimate of Kaplan and Meier (1958) has been generally accepted as a substitute for the empirical distribution function, since it is the nonparametric maximum likelihood estimator (NPMLE) [Cox and Oakes (1984), page 48] and possesses the properties of self-consistency [Efron (1967)] asymptotic normality [Breslow and Crowley (1974)], and asymptotic efficiency [Wellner (1982)]. In cases other than right censoring, it is natural to search for estimates which possess similar properties. For detailed discussions, see Tsai and Crowley (1985) and Gill (1989).

In the case where observations have the possibility of being censored either from right or left, Turnbull (1974) proposed a self-consistent algorithm to find the NPMLE for the underlying distribution. Chang and Yang (1987) proved the asymptotic consistency of self-consistent estimates under mild conditions on the censoring for continuous distributions with support $(0, \infty)$, and Chang (1990) obtained the asymptotic normality on compact intervals under a quite strong additional condition on the censoring. Some related models were studied by Ayer, Brunk, Ewing, Reid and Silverman (1955), Groeneboom (1987) and Samuelsen (1989). In this paper, we shall generalize the consistency result to noncontinuous distributions with an arbitrary support, establish the asymptotic normality on the entire range of the lifetime under weaker conditions on censoring and show that Turnbull's estimator is asymptotically efficient.

2. Main results. Let X_i , $i \geq 1$, be independent identically distributed (i.i.d.) random variables with a common survival function S_X . Independent of

Received December 1989; revised April 1992.

¹Research partially supported by Fonds pour la Formation de chercheurs et L'Aide à la Recherche 91NC0531.

²Research partially supported by NSF Grant DMS-89-16180 and Army Research Office Grant DAAL03-91-G-0045.

AMS 1991 subject classifications. Primary 62G05, 62G30; secondary 62E20, 62G20.

Key words and phrases. Survival distribution, censored data, self-consistency, consistency, asymptotic normality, weak convergence, efficiency.

the X_i 's let $Y_i \geq Z_i$, $i \geq 1$, be i.i.d. pairs of censoring times with possibly defective marginal survival functions S_Z and S_Y . For $i \geq 1$ set

$$(2.1) \quad \begin{aligned} V_i &= \max(\min(X_i, Y_i), Z_i), \\ \delta_i &= \begin{cases} 1, & \text{if } Z_i < X_i \leq Y_i, \\ 2, & \text{if } V_i = Y_i < X_i \text{ (right censoring),} \\ 3, & \text{if } V_i = Z_i \geq X_i \text{ (left censoring).} \end{cases} \end{aligned}$$

We study asymptotic properties of self-consistent estimators for S_X based on (V_i, δ_i) , $1 \leq i \leq n$.

Let $Q_n^{(j)}$, $1 \leq j \leq 3$, Q_n and $Q_n^{(0)}$ be the empirical version of

$$(2.2) \quad \begin{aligned} Q^{(j)}(t) &= \Pr\{V > t, \delta = j\}, \quad 1 \leq j \leq 3, \\ Q &= (Q^{(1)}, Q^{(2)}, Q^{(3)}), \quad Q^{(0)} = \sum_{j=1}^3 Q^{(j)}. \end{aligned}$$

Set $K = S_Y - S_Z$. It follows from (2.1) that $\Pr\{\delta = 1|X = t\} = K(t-)$ and

$$(2.3) \quad \begin{aligned} dQ^{(1)}(t) &= K(t-) dS_X(t), \quad dQ^{(2)} = S_X dS_Y, \\ dQ^{(3)} &= (1 - S_X) dS_Z. \end{aligned}$$

By Tsai and Crowley [(1985), page 1328], the estimate S_n is self-consistent if

$$(2.4) \quad S_n(t) = Q_n^{(0)}(t) - \int_{u \leq t} \frac{S_n(t)}{S_n(u)} dQ_n^{(2)}(u) + \int_{t < u} \frac{1 - S_n(t)}{1 - S_n(u)} dQ_n^{(3)}(u),$$

where $\int_{u \leq t} = 0$ ($\int_{t < u} = 0$) if $S_n(t) = 0$ [$S_n(t) = 1$]. The NPMLE of S_X is self-consistent [Turnbull (1974)], but a self-consistent estimate is not necessarily an NPMLE. For example, with four observations (1, 1), (2, 2), (3, 3) and (4, 3) from (V, δ) , S_n defined by $dS_n(1) = -2/3$ and $dS_n(4) = -1/3$, is self-consistent but not an NPMLE, which essentially puts mass 1/2 at 1 and 3. Among other things, an NPMLE must satisfy

$$(2.5) \quad \begin{aligned} Q_n^{(2)}(-\infty) - Q_n^{(2)}(a_n-) &= - \int_{u < a_n} \frac{dQ_n^{(2)}(u)}{S_n(u)}, \\ Q_n^{(3)}(b_n) &= - \int_{b_n < u} \frac{dQ_n^{(3)}(u)}{1 - S_n(u)}, \end{aligned}$$

where $a_n = \min\{V_i: \delta_i = 1 \text{ or } 3\}$ and $b_n = \max\{V_i: \delta_i = 1 \text{ or } 2\}$. This constraint is useful later.

Let $\|h\| = \sup_t |h(t)|$ be the supremum norm throughout the paper. Chang and Yang (1987) proved $\|S_n - S_X\| \rightarrow 0$ a.s. for S_n satisfying (2.4) under the assumptions that

$$(2.6) \quad K(t-) = \Pr\{\delta = 1|X = t\} > 0$$

for all $t > 0$, that S_X , S_Y and S_Z are all continuous, and that the support of

X is $(0, \infty)$. Our first result gives the strong uniform consistency under a single condition on the censoring.

THEOREM 1. *Suppose (2.6) holds on $\{t: S_X(t) < 1 \text{ and } S_X(t-) > 0\}$. Then, $\|S_n - S_X\| \rightarrow 0$ a.s.*

Since $Q_n \rightarrow Q$ uniformly and S_n satisfies (2.4), $S_{n_k}(t) \rightarrow S(t)$ for each t as $n_k \rightarrow \infty$ implies

$$(2.7) \quad S(t) = Q^{(0)}(t) - \int_{u \leq t} \frac{S(t)}{S(u)} dQ^{(2)}(u) + \int_{t < u} \frac{1 - S(t)}{1 - S(u)} dQ^{(3)}(u).$$

Theorem 1 is proved in Section 3 via the uniqueness of the solution of (2.7). The method of Chang and Yang [(1987), (2.5) and Lemma 4.1] cannot be used, because their fundamental integral equation system is not continuous under pointwise convergence.

A sequence of estimators $\{S_n\}$ is asymptotically normal if $\sqrt{n}(S_n - S_X)$ converges in distribution to a Gaussian process in a suitable metric space of functions. In this paper, a Banach space is always equipped with its ball σ -algebra, and random elements and convergence in distribution are defined as in Pollard [(1984), page 65]. For any survival function S define linear operators A_S , R_S , K and B_S by

$$(2.8) \quad \begin{aligned} (A_S h)(t) &= \int_{u \leq t} \frac{S(t)}{S(u)} h(u) dS_Y(u) \\ &\quad + \int_{t < u} \frac{1 - S(t)}{1 - S(u)} h(u) dS_Z(u), \end{aligned}$$

$$(2.9) \quad R_S = K - A_S, \quad (Kh)(t) = K(t)h(t), \quad K(t) = S_Y(t) - S_Z(t),$$

$$(2.10) \quad \begin{aligned} (B_S(h^{(1)}, h^{(2)}, h^{(3)}))(t) &= \sum_{j=1}^3 h^{(j)}(t) - \int_{u \leq t} \frac{S(t)}{S(u)} dh^{(2)}(u) \\ &\quad + \int_{t < u} \frac{1 - S(t)}{1 - S(u)} dh^{(3)}(u), \end{aligned}$$

where integrating by parts should be used in (2.10) whenever necessary. Domains of these operators include all bounded measurable functions, and we shall extend those of A_S and R_S under the conditions of Theorem 2. By (2.3) and (2.8), $A_{S_n}(S_n - S_X) = B_{S_n}Q - Q^{(0)} + S_n(S_Y - 1) + (1 - S_n)S_Z$. Since $S_n = B_{S_n}Q_n$ by (2.4) and $Q^{(0)} = KS_X + S_Z$ by (2.1),

$$(2.11) \quad R_{S_n}\xi_n = B_{S_n}W_n, \quad \xi_n = \sqrt{n}(S_n - S_X), \quad W_n = \sqrt{n}(Q_n - Q).$$

Let $(D, \|\cdot\|)$ be the Banach space of all real-valued functions defined on $(-\infty, \infty)$ which are right-continuous and have left limits at $x \leq \infty$ and right limit at $-\infty$, and $(D[a, b], \|\cdot\|)$ the restrictions of $h \in D$ on $[a, b]$, where

$a = \sup\{t: S_X(t) = 1\}$ and $b = \inf\{t: S_X(t) = 0\}$. Define Banach spaces

$$\begin{aligned} (D_0[a, b], \|\cdot\|) &= \{h \in D[a, b]: S_X(x) = 1 \Rightarrow h(x) = 0, \\ &\quad S_X(x-) = 0 \Rightarrow h(x-) = 0\}, \\ (D_K[a, b], \|\cdot\|_K) &= \{h: Kh \in D[a, b]\}, \quad \|h\|_K = \|Kh\|, \\ (D_0^3, \|\cdot\|_3) &= \{h \in D \otimes D \otimes D: B_{S_X}h \in D_0[a, b]\}, \\ \|(h^{(1)}, h^{(2)}, h^{(3)})\|_3 &= \sum_{j=1}^3 \|h^{(j)}\|. \end{aligned}$$

Since Q_n is the empirical version of Q and by (2.10) $B_{S_X}(Q_n - Q) \in D_0[a, b]$, it follows from (2.2) that

$$(2.12) \quad W_n \rightarrow_{\mathcal{D}} W = (W^{(1)}, W^{(2)}, W^{(3)}) \text{ in } D_0^3$$

with $EW^{(j)}(t) = 0$ and $EW^{(j)}(t)W^{(k)}(s) = Q^{(j)}(\max(t, s))I\{j = k\} - Q^{(j)}(t)Q^{(k)}(s)$.

THEOREM 2. For each n let S_n be a solution of (2.4) such that either (2.5) holds or $S_n - S_X \in D_0[a, b]$. Suppose (2.6) holds on the set $\{t: S_X(t) < 1, S_X(t-) > 0\}$ and

$$(2.13) \quad \int_{\tau < S_X(u) < 1} \frac{-dS_Y(u)}{S_Y(u) - S_Z(u)} + \int_{0 < S_X(u) < \tau} \frac{-dS_Z(u)}{S_Y(u) - S_Z(u)} < \infty, \\ \forall 0 < \tau < 1.$$

Then $R_{S_X}^{-1}$, the inverse of R_{S_X} in (2.9), exists as a bounded operator from $D_0[a, b]$ to $D_K[a, b]$, and

$$(2.14) \quad \sqrt{n}(S_n - S_X) = \xi_n \rightarrow_{\mathcal{D}} \xi = R_{S_X}^{-1}B_{S_X}W \text{ in } D_K[a, b],$$

where W is the Gaussian process in (2.12) and $\Pr\{B_{S_X}W = R_{S_X}\xi \in D_0[a, b]\} = 1$.

COROLLARY 1. Let S_n be a solution of (2.4). If $\inf_{0 < S_X(t) < 1} K(t-) > 0$, then $\xi_n \rightarrow_{\mathcal{D}} R_{S_X}^{-1}B_{S_X}W$ in D .

Theorem 2 is proved in Section 4. Conditions (2.4) and (2.5) hold for all NPMLE's. The condition $S_n - S_X \in D_0[a, b]$ says that the support of S_n is contained in that of S_X , which holds if $S_n(0) = 1$ and the support of S_X is $(0, \infty)$. Here the invertibility of R_S means $R_S R_S^{-1}h = h$ on $D_0[a, b]$. By (2.9), R_{S_X} is defined on the entire space $D_K[a, b]$ if and only if (2.13) holds. By (2.6) and (2.13),

$$(2.15) \quad \inf\{K(t): \tau < S_X(t) \leq 1 - \tau\} > 0, \quad \forall 0 < \tau < 1/2$$

and $\|h\|_K = 0 \Rightarrow \|h\| = 0$. Therefore, (2.14) is equivalent to $K\xi_n \rightarrow_{\mathcal{D}} KR_{S_X}^{-1}B_{S_X}W$ in $D[a, b]$.

Chang (1990) proved the asymptotic normality of $\xi_n(t)$ as processes on $[0, T]$ under the conditions of Chang and Yang (1987) for the asymptotic consistency

and the additional conditions that

$$(2.16) \quad \Pr\{Z = 0\} > 0, \quad \Pr\{0 < Z < \delta\} = 0 \quad \text{and} \quad \Pr\{Z > T\} = 0$$

for some $0 < \delta \leq T < \infty$. Compared with his results, Theorem 2 gives the convergence on the entire support of X under weaker and more appealing conditions. The asymptotic normality of the product limit estimate on $(0, \infty)$ was proved by Gill (1983). Under the conditions of Chang (1990), $K(t)$ is continuous and (2.6) and (2.16) hold, so that $\inf_{0 \leq t \leq T} K(t) > 0$ and $S_Z(T) = 0$ for some $0 < S_X(T) < 1$, which imply (2.13). Chang [(1990), page 393] remarked that the purpose of his condition (2.16) was to avoid singularity of certain integral equations and it was not clear whether his results were valid without (2.16). In the following example we discuss a truncation-censoring model in which (2.13) is always satisfied when S_X is identifiable. Truncation models have been considered by Linden-Bell (1971), Woodroffe (1985) and Lagakos, Barraj and De Gruttola (1988) among others.

EXAMPLE 1. Let X^0 , Y^0 and Z^0 be independent random variables. Suppose that the data is completely truncated (no observation) when $Y^0 < Z^0$, and the random variable of interest X^0 is doubly censored by (Y^0, Z^0) when $Y^0 \geq Z^0$. Then, the observations (V_i, δ_i) , $1 \leq i \leq n$, are given by (2.1) with

$$\Pr\{X_i \in dx, Y_i \in dy, Z_i \in dz\} = \Pr\{X^0 \in dx\} \Pr\{Y^0 \in dy, Z^0 \in dz | Y^0 \geq Z^0\}.$$

Let S_Y^0 and S_Z^0 be the survival functions of Y^0 and Z^0 , respectively. Then, $dS_Y(u) = \alpha(1 - S_Z^0(u)) dS_Y^0(u)$, $dS_Z(u) = \alpha S_Y^0(u) dS_Z^0(u)$ and $S_Y(u) - S_Z(u) = \alpha(1 - S_Z^0(u)) S_Y^0(u)$, where $\alpha = 1/\Pr\{Y^0 \geq Z^0\}$. Clearly, the survival function S_X is identifiable if and only if $S_Y^0 = 0 \Rightarrow S_X = 0$ and $S_Z^0 = 1 \Rightarrow S_X = 1$, and in this case conditions (2.6) and (2.13) are both satisfied and the asymptotic normality (2.14) holds for the NPMLE. But if $\Pr\{0 < Z^0 < \delta\} > 0$ for all $\delta > 0$ or $\Pr\{Z^0 = 0\} = 0$, then (2.16) does not hold and the result of Chang (1990) does not apply.

We shall also establish the asymptotic efficiency of self-consistent estimators here by proving a Hájek convolution theorem, which extends the results of Beran (1977) and Wellner (1982) to doubly censored data. Given a Banach space, a sequence of estimators $\{\tilde{S}_n\}$, $\tilde{S}_n$ based on (V_i, δ_i) , $1 \leq i \leq n$, is regular if there exists a random element ξ such that $\mathcal{L}(n^{1/2}(\tilde{S}_n - S_{X,n}); Q_{(n)})$ converges in distribution to $\mathcal{L}(\xi; Q)$ for all sequences of survival functions $\{Q_{(n)}\}$ of (V, δ) such that the joint distributions of $(V_1, \delta_1), \dots, (V_n, \delta_n)$ under $Q_{(n)}$ and those under Q are contiguous [Beran (1977)], where $\mathcal{L}(\cdot; Q)$ is the distribution under the probability measure corresponding to Q and $S_{X,n} \sim \mathcal{L}(X; Q_{(n)})$.

THEOREM 3. Suppose the conditions of Theorem 2 hold. If $\{\tilde{S}_n\}$ is regular in $D_K[a, b]$, then

$$\mathcal{L}(n^{1/2}(\tilde{S}_n - S_X); Q) \rightarrow_{\mathcal{D}} \mathcal{L}(\tilde{\xi}; Q) = \mathcal{L}(\xi + \zeta; Q) \quad \text{in } D_K[a, b],$$

where ξ is as in Theorem 2 and ζ is some process independent of ξ .

The proof of Theorem 3 is analogous to those in Beran (1977). We shall give a sketch in Section 5.

3. Proof of Theorem 1. Lemma 1 below, proved in the Appendix, will be used to show that S_X is completely determined by Q via (2.7), so that we can regard it as an identifiability result. It has two parts: Part (i) deals with functions S and h which are not necessarily right-continuous, while part (ii), used in Section 4, concerns functions h whose support is larger than that of S . A set J of real numbers does not have a limit point from left if every nonempty subset of J contains its maximum.

LEMMA 1. *Let S be a $[0, 1]$ -valued nonincreasing function and h be a function such that*

$$(3.1) \quad \begin{aligned} h(t)K(t) &= \int_{u \leq t} \frac{S(t)}{S(u)} h(u) dS_Y(u) \\ &\quad + \int_{t < u} \frac{1 - S(t)}{1 - S(u)} h(u) dS_Z(u), \quad \forall t. \end{aligned}$$

(i) *Suppose (2.6) holds on the set $\{t: 0 < S(t) < 1\}$. Then, $h(t) = 0$ for all t , provided that*

$$(3.2) \quad h(t+) \neq h(t) \Rightarrow S(t+) < S(t) \quad \text{on } \{t: 0 < S(t) < 1\},$$

$$(3.3) \quad h(t) = 0 \quad \text{on } \{t: S(t) = 0 \text{ or } S(t) = 1\}.$$

(ii) *Let $J_X = \{t: 0 < S_X(t) < 1\}$. Suppose (2.6) holds on J_X and the set $J_X \cap \{t: S_Y(t) \leq S_Z(t-)\}$ does not have a limit point from left. If S is right-continuous with $\{t: 0 < S(t) < 1\} \subset J_X$, h is right-continuous for $t \in J_X$ and $h(t) = 0$ for $t \notin J_X$, then $h(t) = 0$ for all t .*

PROOF OF THEOREM 1.

STEP 1 [Uniqueness of the solution of (2.7)]. We shall first prove $S = S_X$ under

$$(3.4) \quad S_X(t) = 0 \Rightarrow S(t) = 0 \quad \text{and} \quad S_X(t) = 1 \Rightarrow S(t) = 1.$$

Set $h = S - S_X$. We only need to verify the conditions of Lemma 1(i). It can be shown in the same manner as in the derivation of (2.11) that (2.7) implies (3.1). By (3.4) and the condition of Theorem 1, (2.6) holds on the set $\{t: 0 < S(t) < 1\}$. Since $S_X(t)$ is right-continuous, (3.2) is obvious. By (2.6) $dQ^{(1)}(t) = K(t-)dS_X(t)$ and $K(t-) > 0$, so that by (2.7) $S(t) = 0 \Rightarrow Q^{(1)}(t) = 0 \Rightarrow S_X(t) = 0$ and $S(t) = 1 \Rightarrow Q^{(1)}(t) = Q^{(1)}(-\infty) \Rightarrow S_X(t) = 1$, which implies (3.3). Therefore, $S = S_X$.

Step 1 is completed if we can drop (3.4). To this end we need

$$(3.5) \quad \int_{b \leq u} \frac{dQ^{(3)}(u)}{1 - S(u)} = \int_{b \leq u} dQ^{(3)}(u), \quad \int_{u < a} \frac{dQ^{(2)}(u)}{S(u)} = \int_{u < a} dQ^{(2)}(u).$$

Define $K_S(t) = 1 + \int_{u \leq t} S^{-1}(u) dQ^{(2)}(u) + \int_{t < u} (1 - S(u))^{-1} dQ^{(3)}(u)$. It follows from (2.7) that $K_S(t-)dS(t) = dQ^{(1)}(t)$ and $S(t)K_S(t) = Q^{(0)}(t) + \int_{t < u} (1 - S(u))^{-1} dQ^{(3)}(u)$. Since $Q^{(2)}(b-) = Q^{(1)}(b) = 0$, $K_S(b-)S(b) = Q^{(3)}(b-) + \int_{b \leq u} (1 - S(u))^{-1} dQ^{(3)}(u) \leq 0$. Since $dQ^{(1)}(t) < 0$ at b or near $b-$, $K_S(b-) \geq 0$, and we have the first equation of (3.5). The second one can be obtained in the same manner.

Let $S_0(t) = S(t)I\{0 < S_X(t) < 1\} + I\{S_X(t) = 1\}$. Since (2.7) holds for S , by (3.5) it also holds for S_0 . Since S_0 satisfies (3.4), we have $S_0 = S_X$, which implies $S(t) = S_X(t)$ for $0 < S_X(t) < 1$. If $dS_X(b) = 0$, then $S(b-) = S_X(b-) = 0$. Otherwise, (2.7) and (3.5) imply $K_S(b-)S(b) = 0$, and $dQ^{(1)}(b) < 0$ ensures $K_S(b-) > 0$. In any case we have the first part of (3.4), and the proof for the second part is omitted.

STEP 2 (Uniform consistency). By (2.4) all limit points of S_n must satisfy (2.7), so that by Step 1 and the Helly-Bray selection theorem we have $S_n(t) \rightarrow S_X(t)$ a.s. $\forall t$. If $dS_X(t) < 0$, then by (2.4) and (2.6),

$$\frac{dQ_n^{(1)}(t)}{dS_n(t)} \leq 1 + \int_{u < t-\varepsilon} \frac{dQ_n^{(2)}(u)}{S_n(u)} + \int_{t \leq u} \frac{dQ_n^{(3)}(u)}{1 - S_n(u)} \rightarrow \frac{dQ^{(1)}(t)}{dS_X(t)}$$

as $n \rightarrow \infty$ and then $\varepsilon \rightarrow 0+$, which implies $|dS_n(t)| \geq (1 - o(1))|dS_X(t)|$, since $dQ_n^{(1)}/dQ^{(1)}(t) \rightarrow 1$. Hence, $\|S_n - S_X\| \rightarrow 0$ a.s. $\square$

4. Proof of Theorem 2. Let $S_{X,m}, S_{Y,m}, S_{Z,m}$, $m \geq 1$, and S be survival functions such that

$$(4.1) \quad \begin{aligned} S - S_X &\in D_0[a, b], \quad S(t) = 1 \Rightarrow S_{X,m}(t) = 1, \\ S(t-) &= 0 \Rightarrow S_{X,m}(t-) = 0, \end{aligned}$$

$$(4.2) \quad \begin{aligned} \|S_{X,m} - S\| &\rightarrow 0, \quad \|S_{Y,m} - S_Y\| \rightarrow 0, \quad \|S_{Z,m} - S_Z\| \rightarrow 0, \\ K_m &= S_{Y,m} - S_{Z,m} \geq 0. \end{aligned}$$

LEMMA 2. Let h_m, g_m , $m \geq 1$, and g be functions in $D_0[a, b]$ such that $\|g_m - g\| \rightarrow 0$ and $R_m h_m = g_m$, where $R_m = K_m - A_m$, and A_m , R_m , and K_m are defined as in (2.8)–(2.10) with (S_X, S_Y, S_Z) replaced by $(S_{X,m}, S_{Y,m}, S_{Z,m})$. Suppose that the conditions of Theorem 2 hold and

$$(4.3) \quad \lim_{\tau \rightarrow 0+} \sup_m \left[\int_{1-\tau < S_X(u) < 1} \frac{-dS_{Y,m}(u)}{K_m(u)} + \int_{0 < S_X(u) < \tau} \frac{-dS_{Z,m}(u)}{K_m(u)} \right] = 0.$$

Let R_S be given by (2.9). Then there exists $h \in D_K[a, b]$ such that $\|K_m h_m - Kh\| \rightarrow 0$ and $R_S h = g$.

Lemma 2 is proved in the Appendix. Theorem 2 is proved via strong continuity of linear operators indexed by survival functions in the metric space $\Theta = \{S: S - S_X \in D_0[a, b]\}$ with the distance $\|S - S'\|$. In the sequel, a function is said to be simple if it is a step function with finite number of jumps.

PROOF OF THEOREM 2. We consider the case $S_n \in \Theta$ in Steps 1–4 and (2.5) in Step 5.

STEP 1 (Existence of R_S^{-1} as a linear operator from $D_0[a, b]$ to $D_K[a, b]$, $\forall S \in \Theta$). Let $S_{X,m}$, $S_{Y,m}$, and $S_{Z,m}$ be finite discrete survival functions satisfying the conditions of Lemma 2 and $K_m(t-) > 0$ for $0 < S_X(t) < 1$. The existence of such survival functions is guaranteed by (2.13) and (2.6). For any $g \in D_0[a, b]$ let g_m be simple functions in $D_0[a, b]$ with $\|g_m - g\| \rightarrow 0$. Also, let Γ_m be the finite set of discontinuities of $S_{X,m}$, $S_{Y,m}$, $S_{Z,m}$ or g_m , and D_m the space of simple functions in $D_0[a, b]$ with jumps only at Γ_m . Since $R_m D_m \subset D_m$ and D_m is a finite-dimensional space, it follows from Lemma 1(ii) that R_m is a one-to-one mapping from D_m onto D_m , so that $R_m h_m = g_m$ has a solution $h_m \in D_m$. Since $\|g_m - g\| \rightarrow 0$, by Lemma 2 $R_S h = g$ has a unique solution $h \in D_K[a, b]$. Define $h = R_S^{-1}g$.

STEP 2 (Strong continuity of $\{R_S^{-1}: S \in \Theta\}$). Let $g'_m \in D_0[a, b]$ and S_m in Θ be such that $\|g'_m - g\| \rightarrow 0$ and $\|S_m - S\| \rightarrow 0$. It suffices to show $\|KR_{S_m}^{-1}g'_m - KR_S^{-1}g\| \rightarrow 0$, since $S_m = S$ gives the boundedness of R_S^{-1} and $g'_m = g$ gives the strong continuity. As in Step 1 we may obtain $S_{X,m}$, $S_{Y,m}$, $S_{Z,m}$, h_m , g_m and $\varepsilon_m \rightarrow 0$ such that $R_m h_m = g_m$, $\|K_m h_m - KR_{S_m}^{-1}g'_m\| \leq \varepsilon_m$, $\|S_{X,m} - S_m\| \leq \varepsilon_m$ and $\|g_m - g'_m\| \leq \varepsilon_m$. Since $\|g_m - g\| \leq \varepsilon_m + \|g'_m - g\| \rightarrow 0$ and $\|S_{X,m} - S\| \leq \varepsilon_m + \|S_m - S\| \rightarrow 0$, it follows from Lemma 2 that $\|K_m h_m - KR_S^{-1}g\| \rightarrow 0$, which implies

$$\|KR_{S_m}^{-1}g'_m - KR_S^{-1}g\| \leq \varepsilon_m + \|K_m h_m - KR_S^{-1}g\| \rightarrow 0.$$

STEP 3 (Strong continuity of $\{B_S, S \in \Theta\}$). Let h be a simple function in D_0^3 . Since $S - S_X \in D_0[a, b]$, by (2.10) $B_S h \rightarrow B_{S_X} h$ in $D_0[a, b]$ as $\|S - S_X\| \rightarrow 0$. Since $\|B_S\| \leq 2$ and the collection of simple functions is dense in D_0^3 , we have the strong continuity.

STEP 4 (Conclusion). By Steps 2 and 3, $\{H_S = R_S^{-1}B_S, S \in \Theta\}$ is strongly continuous, so that by Theorem 1 and the Banach–Steinhaus theorem $\sup\{\|H_{S_n}h - H_S h\|_K: h \in C(\varepsilon)\} \rightarrow 0$ as $n \rightarrow \infty$ and then $\varepsilon \rightarrow 0+$ a.s. for all compact set $C \subset D_0^3$, where $C(\varepsilon) = \{h \in D_0^3: \|h - h'\|_3 < \varepsilon \text{ for some } h' \in C\}$. Since $W_n \rightarrow_D W$ in D_0^3 , $\{W_n\}$ is uniformly tight [Pollard (1984), page 81], so that $\|\xi_n - H_{S_X} W_n\|_K = \|(H_{S_n} - H_{S_X})W_n\|_K = o_P(1)$, which implies (2.14) by (2.11) and the continuous mapping theorem [Pollard (1984), page 70].

STEP 5 (Assume (2.5) holds for S_n). Let $a'_n \in [a, a_n)$ and $b'_n \in (b_n, b]$, where (c, c) and $[c, c)$ are defined to be $\{c\}$. Set $S'_n(t) = S_n(t)I\{a'_n \leq t < b'_n\} + I\{t < a'_n\}$. Then, (2.4) holds for S'_n and $S'_n - S_X \in \Theta$, so that $\sqrt{n}(S'_n - S_X)$ converges in distribution in $D_K[a, b]$. The conclusion follows if we choose a'_n and b'_n such that $2K(a'_n)|\xi_n(a'_n)| \geq \sup_{a \leq t \leq a'_n} K(t)|\xi_n(t)|$ and $2K(b'_n -)|\xi(b'_n -)| \geq \sup_{b'_n \leq t \leq b} K(t)|\xi_n(t)|$. $\square$

PROOF OF COROLLARY 1. Let $a'_n = \min\{t: dQ_n^{(1)}(t) < 0\}$ and $b'_n = \max\{t: dQ_n^{(1)}(t) < 0\}$. Similar to Step 1 of the proof of Theorem 1 we can show that $S_n - S_X \in D_0[a, b]$ if $Q_n^{(2)}(b'_n -) = 0$ and $Q_n^{(3)}(a'_n -) = Q_n^{(3)}(-\infty)$. Under our assumption, it can be proved that $Q^{(2)}(b_n -) = o(1/n)$ and $Q^{(3)}(-\infty) - Q^{(3)}(a'_n -) = o(1/n)$. Since the size of jump is at least $1/n$, $\Pr\{S_n - S_X \in D_0[a, b]\} \rightarrow 1$. $\square$

5. Proof of Theorem 3. Let μ be a bounded linear functional on $D_K[a, b]$. By the argument of Beran (1977), it suffices to prove the existence of random variables $\eta = \eta_\mu(V, \delta) \in L^2(Q)$ and normal random variables $\{Z(\alpha), \alpha \in L^2(Q), E\alpha = 0\}$ with $EZ(\alpha) = 0$ and $EZ(\alpha)Z(\alpha') = E\alpha\alpha'$ such that

$$(5.1) \quad \begin{aligned} E \exp[i\mu(\tilde{\xi})] &= E \exp[i\mu(\tilde{\xi}) - iE\alpha\eta + Z(\alpha) - E\alpha^2/2], \\ E|\mu(\xi)|^2 &= \text{Var}(\eta). \end{aligned}$$

The covariance structure of $Z(\alpha)$ ensures that $Z(\alpha)$ is linear in α and $Z(\eta_{\mu'}) = \mu'(\xi) \forall \mu'$, for a version of ξ . The convolution is obtained by setting $Z(\alpha) = i\mu'(\xi)$ with $\alpha = i\eta_{\mu'}$. To prove (5.1), let $\alpha = \alpha(V, \delta)$ be a bounded function of (V, δ) with $E\alpha = 0$ such that $\alpha(t, j) = 0$ for $S_X(t) < \varepsilon$ or $S_X(t) > 1 - \varepsilon$. Define $dQ_{(n)}^{(j)}(t) = [1 + \alpha(t, j)/\sqrt{n}] dQ^{(j)}(t)$ for large n and $1_{(V, \delta)}^{(j)}(t) = I\{V > t, \delta = j\}$. Then, $Q = E1_{(V, \delta)}, 1_{(V, \delta)} - Q \in D_0^3$, $\sqrt{n}(Q_{(n)} - Q) = E\alpha(V, \delta)(1_{(V, \delta)} - Q)$, and, as in the proof of Theorem 2, $\mu(\sqrt{n}(S_{X,n} - S_X)) \rightarrow \mu(H_{S_X}E\alpha(V, \delta)(1_{(V, \delta)} - Q)) = E\alpha\eta$, where $\eta = \mu(H_{S_X}(1_{(V, \delta)} - Q))$ and $H_S = R_S^{-1}B_S$. Since $\{Q_{(n)}\}$ and $\{Q\}$ are contiguous, we can show as in Beran (1977) the existence of $Z(\alpha)$ satisfying the first equation of (5.1). For the second one, we have $E|\mu(\xi)|^2 = E|\mu(H_{S_X}W)|^2 = E|\mu(H_{S_X}(1_{(V, \delta)} - Q))|^2 = \text{Var}(\eta)$. $\square$

APPENDIX

PROOF OF LEMMA 1. Proof of (i). Since $d(UV) = U dV + V_- dU$, by (3.1) and (3.3) for $0 < S(t) < 1$,

$$(A.1) \quad K(t) dh(t+) = g(t) dS(t+), \quad K(t-) dh(t) = g(t-) dS(t),$$

where $dh(t) = h(t) - h(t-)$ and $dh(t+) = h(t+) - h(t)$ at discontinuities for all h , and

$$(A.2) \quad g(t) = \int_{u \leq t} \frac{h(u)}{S(u)} dS_Y(u) - \int_{t < u} \frac{h(u)}{1 - S(u)} dS_Z(u).$$

Assume $h(t_0) > 0$ and $0 < S(t_0) < 1$ at some point t_0 . Our goal is to establish a contradiction. Define

$$\begin{aligned} t_1 &= \sup\{t \leq t_0: h(t) \leq 0\}, & t_2 &= \inf\{t \geq t_0: h(t) \leq 0\}, \\ J &= \{t: h(t) > 0, t_1 \leq t \leq t_2\}. \end{aligned}$$

Then, $t_0 \in J$ and $(t_1, t_2) \subset J \subset [t_1, t_2]$.

STEP 1. Show that $g(t) = g(t-) = 0$ on J . By (A.2) $g(t)$ is a right-continuous function with

$$(A.3) \quad dg(t) = h(t) \left[\frac{dS_Y(t)}{S(t)} + \frac{dS_Z(t)}{1 - S(t)} \right] \leq 0 \quad \text{on } J.$$

To show that $g(t) \leq 0$ and $g(t-) \leq 0$ in J , we have four cases; the “greater than or equal to” part is similar and omitted.

CASE 1. $t_1 = -\infty$ or $S(t_1) = 1$. By (3.3) $\int_{u \leq t} (h(u)/S(u)) dS_Y(u) \leq 0$ in J , which implies $\int_{t < u} (1 - S(u))^{-1} h(u) dS_Z(u) \geq 0$ by (3.1). Since $t_1 \notin J$, $g(t) \leq 0$ and $g(t-) \leq 0$ on J by (A.2).

For Cases 2–4, we show $g(t_1-) \leq 0$ for $t_1 \in J$ and $g(t_1) \leq 0$ for $t_1 \notin J$, which will imply $g(t) \leq 0$ and $g(t-) \leq 0$ on J by (A.3).

CASE 2. $h(t_1) > 0$, $t_1 \in J$. Since $K(t_1-) dh(t_1) > 0$, $g(t_1-) < 0$ by (A.1).

CASE 3. $h(t_1) \leq 0$, $h(t_1+) > 0$, and $S(t_1) < 1$, $t_1 \notin J$. Here (3.2) implies $dS(t_1+) < 0$, and (A.1) implies $g(t_1) \leq 0$.

CASE 4. $h(t_1) \leq 0$ and $h(t_1+) = 0$, $t_1 \notin J$. Since $t_1 < t_0$, there exists $\{t_n\} \subset J$ with $t_n \downarrow t_1$ and $dh(t_n) > 0$ or $dh(t_n+) > 0$. Therefore, $g(t_n-) \leq 0$ or $g(t_n) \leq 0$ by (A.1), so that $g(t_1) \leq 0$ by the right continuity of g .

STEP 2. Find a contradiction. Since $h > 0$ on J , by Step 1 and (A.3),

$$(A.4) \quad dS_Y(t) = dS_Z(t) = 0 \quad \text{and} \quad K(t) = K(t-) = \text{constant} > 0 \quad \text{on } J.$$

By (A.1), Step 1, and (A.4), we have $dh(t) = dh(t+) = 0$ on J , so that

$$(A.5) \quad h(t) = h(t_0) > 0 \quad \text{on } J \quad \text{and} \quad t_0 \in J = (t_1, t_2).$$

CASE 1. $S(t_1) < 1$. By (A.5) $h(t_1) \leq 0$ and $h(t_1+) = h(t_0) > 0$. Since $K(t_1) > 0$ by (A.4), it follows from (A.1) that $g(t_1+) < 0$, which is a contradiction to Step 1.

CASE 2. $S(t_2) > 0$. By (A.5) $h(t_2) \leq 0$ and $h(t_2-) = h(t_0) > 0$, so that by (A.1) and (A.4) $g(t_2-) > 0$, which is again a contradiction to Step 1.

CASE 3. $S(t_1) = 1$ and $S(t_2) = 0$. It follows from (3.3) that the right-hand side of (3.1) is nonpositive, so that $h(t)K(t) \leq 0$ for all t . However, $h(t)K(t) > 0$ on J by (A.4) and (A.5).

Proof of (ii). It suffices to show that (3.3) holds. Let $t_1 = \max\{t: h(t) \neq 0, S_Y(t) - S_Z(t-) \leq 0, S(t) = 0\}$ if the set is not empty and $t_1 = \inf\{t: S(t) = 0\}$ otherwise. Since $\{t: h(t) \neq 0, S_Y(t) - S_Z(t-) \leq 0\}$ does not have a limit point from left, the maximum is reached for the nonempty case. For $t \geq t_1$ by (3.1)

$K(t)h(t) = \int_{t < u} h(u) dS_Z(u)$. Assume $h(t_2) > 0$ for some $t_2 > t_1$. We shall find a contradiction. Let $t_3 = \inf\{t: h(t) \leq 0, t \geq t_2\}$. By the right continuity of h and (2.6), h has to change sign on the right of t_2 , so that $S_X(t_3) > 0$. Since $K(t)h(t)$ is nondecreasing in $[t_2, t_3]$, by (3.1)

$$\begin{aligned} 0 &< h(t_3 -)K(t_3 -) = h(t_3)K(t_3) + h(t_3) dS_Z(t_3) \\ &= h(t_3)[S_Y(t_3) - S_Z(t_3 -)]. \end{aligned}$$

This gives a contradiction to the definition of t_1 and t_3 . Therefore, $h(t) = 0$ for $t \geq t_1$ and $t_1 = \inf\{t: S(t) = 0\}$ by its definition, so that $S(t) = 0 \Rightarrow h(t) = 0$. Similarly, $S(t) = 1 \Rightarrow h(t) = 0$. $\square$

PROOF OF LEMMA 2. A sequence of functions is totally bounded if every subsequence contains a uniformly convergent further subsequence. Basically we shall establish the total boundedness of $K_m h_m$ and then prove that there exists exactly one cluster point Kh . Define

$$\begin{aligned} v_m^+(t) &= \int_{t < u} \frac{1 - S_{X,m}(t)}{1 - S_{X,m}(u)} h_m(u) dS_{Z,m}(u), \\ v_m^-(t) &= \int_{u \leq t} \frac{S_{X,m}(t)}{S_{X,m}(u)} h_m(u) dS_{Y,m}(u). \end{aligned}$$

STEP 1. For a fixed $0 < \tau_0 < 1$ establish the total boundedness of $v_m^+(t)I\{S(t) \leq \tau_0\}$ and $v_m^-(t)I\{S(t) > \tau_0\}$ for the case $\|K_m h_m\| \leq 1$. Since $S - S_X \in D_0[a, b]$, there exists $0 < \tau < 1$ such that

$$(A.6) \quad \{S(t) > \tau_0\} \subset \{S_X(t) > \tau\} \quad \text{and} \quad \{S(t) \leq 1 - \tau_0\} \subset \{S_X(t) \leq 1 - \tau\}.$$

It follows from (4.1)–(4.3) and (2.15) that

$$\sup_{S_X(t) > \tau} \left| \int_{u \leq t, S_X(u) < 1} \frac{dS_{Y,m}(u)}{K_m(u)} - \int_{u \leq t, S_X(u) < 1} \frac{dS_Y(u)}{K(u)} \right| = \varepsilon_m \rightarrow 0.$$

Let $s < t$, $S_X(s) < 1$ and $S(t) > \tau_0$. Since $\|K_m h_m\| \leq 1$, by (A.6)

$$\begin{aligned} &|v_m^-(t)/S_{X,m}(t) - v_m^-(s)/S_{X,m}(s)| \\ &= \left| \int_{s < u \leq t} (S_{X,m}(u))^{-1} h_m(u) dS_{Y,m}(u) \right| \\ &\leq (\tau_0 - \|S_{X,m} - S\|)^{-1} \left[2\varepsilon_m - \int_{s < u \leq t} (K(u))^{-1} dS_Y(u) \right]. \end{aligned}$$

Since $g_m(t) = h_m(t) = v_m^-(t) = 0$ for $S_X(t) = 1$, by (2.13) the sequence $[v_m^-(t)/S_{X,m}(t)]I\{S(t) > \tau_0\}$ is totally bounded. Since $\|S_{X,m} - S\| \rightarrow 0$, $v_m^-(t)I\{S(t) > \tau_0\}$ is the product of two totally bounded functions and therefore totally bounded itself. The total boundedness of $v_m^+(t)I\{S(t) \leq \tau_0\}$ can be proved similarly.

STEP 2. Assume $\|K_m h_m\| \leq 1$. Verify $\sup\{|v_m^+(t)|: S(t) > 1 - \delta\} = o(1)$ and $\sup\{|v_m^-(t)|: S(t) \leq \delta\} = o(1)$ as $m \rightarrow \infty$ and then $\delta \rightarrow 0+$. There are two cases for the first equation.

CASE 1. $\{S(t) < 1\} \subset \{S_X(t) \leq 1 - \tau\}$ for some $\tau > 0$. Since $1 - S_{X,m}(t) = v_m^+(t) = 0$ for $S(t) = 1$, by (4.3), (2.15) and the dominated convergence theorem we have

$$\begin{aligned} & \sup\{|v_m^+(t)|: S(t) > 1 - \delta\} \\ & \leq \sup_{1-\delta < S(t) < 1} \int_{0 < S_X(u) < 1-\tau} \frac{1 - S_{X,m}(t)}{1 - S_{X,m}(u)} I\{t < u\} \frac{-dS_{Z_m}(u)}{K_m(u)} \\ & \rightarrow \sup_{1-\delta < S(t) < 1} \int_{0 < S_X(u) < 1-\tau} \frac{1 - S(t)}{1 - S(u)} I\{t < u\} \frac{-dS_Z(u)}{K(u)} \rightarrow 0. \end{aligned}$$

CASE 2 (Not case 1). Since $S - S_X \in D_0[a, b]$, we have $S(a) = S_X(a) = 1$, so that $1 - \delta < S(t) < 1$ for small δ implies that t is close to a . Given $\varepsilon > 0$, by Step 1 there exists $\tau > 0$ such that

$$(A.7) \quad \sup_{S(t) > 1-\tau} |g_m(t)| + \sup_{S(t) > 1-\tau} |v_m^-(t)| \leq \varepsilon, \quad \forall m,$$

since $g_m(t) = h_m(t) = v_m^-(t) = 0$ for $t \leq a$ and $\|g_m - g\| \rightarrow 0$. By the definition of v_m^+ and $R_m h_m = g_m$,

$$(A.8) \quad v_m^+(t) = K_m(t) h_m(t) - v_m^-(t) - g_m(t).$$

Assume $v_m^+(t_0) > \varepsilon$ with $S(t_0) > 1 - \tau$. Then, $h_m(t_0) > 0$ by (A.7) and (A.8). Let $t_1 = \inf\{t > t_0: h_m(t) \leq 0\}$. We shall prove that $S(t_1) \leq 1 - \tau$. Similar to the derivation of (A.1) we have

$$\begin{aligned} & K_m(t_1 -)(h_m(t_1) - h_m(t_1 -)) \\ (A.9) \quad & = [v_m^-(t_1 -)/S_{X,m}(t_1 -) - v_m^+(t_1 -)/(1 - S_{X,m}(t_1 -))] dS_{X,m}(t_1) \\ & \quad + dg_m(t_1). \end{aligned}$$

Since $v_m^+(t)$ is nondecreasing in $[t_0, t_1]$, $v_m^+(t_1 -) \geq v_m^+(t_0) > \varepsilon$, so that by (A.9) and (A.8)

$$\begin{aligned} 0 & \geq K_m(t_1 -) h_m(t_1) \\ & \geq K_m(t_1 -) h_m(t_1 -) + [v_m^-(t_1 -)/S_{X,m}(t_1 -)] dS_{X,m}(t_1) + dg_m(t_1) \\ & = v_m^+(t_1 -) + v_m^-(t_1 -) S_{X,m}(t_1)/S_{X,m}(t_1 -) + g_m(t_1) \\ & > \varepsilon - |v_m^-(t_1 -)| - |g_m(t_1)|, \end{aligned}$$

which implies $S(t_1) \leq 1 - \tau$ by (A.7). This proves $h_m(t) > 0$ on the set $\{t_0 \leq t$,

$S(t) > 1 - \tau$, and therefore

$$\begin{aligned} v_m^+(t_0) &\leq \int_{S(u) \leq 1-\tau} \frac{1 - S_{X,m}(t_0)}{1 - S_{X,m}(u)} h_m(u) dS_{Z,m}(u) \\ &\leq - \int_{S(u) \leq 1-\tau} \frac{1 - S_{X,m}(t_0)}{1 - S_{X,m}(u)} \frac{dS_{Z,m}(u)}{K_m(u)}. \end{aligned}$$

Since t_0 is arbitrary, by (4.1)–(4.3) and (2.15), as $\delta \rightarrow 0 +$ and then $\varepsilon \rightarrow 0 +$,

$$\limsup_{m \rightarrow \infty} \sup \{v_m^+(t) : S(t) > 1 - \delta\} \leq \varepsilon - \int_{S(u) \leq 1-\tau} \frac{(\delta/\tau) dS_Z(u)}{K(u)} \rightarrow \varepsilon \rightarrow 0.$$

For the second equation of Step 2, the proof for “Case 1” is similar to that of the first equation and omitted, but “Case 2” is slightly different. Let τ be such that $|v_m^+(t)| + |g_m(t)| \leq \varepsilon$ for $S(t) \leq \tau$ [see (A.7)]. Assume $v_m^-(t_0) > \varepsilon$ for some $S(t_0) \leq \tau$. Then, $h_m(t_0) > 0$. Let $t_1 = \sup\{t < t_0 : h_m(t) \leq 0\}$. Then

$$v_m^-(t_1) - v_m^-(t_1 -) = \frac{dS_{X,m}(t_1)}{S_{X,m}(t_1)} v_m^-(t_1) + \frac{S_{X,m}(t_1 -)}{S_{X,m}(t_1)} h_m(t_1) dS_{Y,m}(t_1) \leq 0,$$

so that $v_m^-(t_1 -) \geq v_m^-(t_1) \geq v_m^-(t_0) > \varepsilon$, which implies $S(t_1 -) > \tau$. The rest of the proof is omitted.

STEP 3. Prove that the equation $R_S h = g$ has at most one solution with $Kh \in D_0[a, b]$ for every g . Since R_S is a linear operator, we assume $g = 0$. It suffices to check the conditions of Lemma 1(ii). Condition (3.1) says $R_S h = 0$ and holds naturally. Since $S - S_X \in D_0[a, b]$, S is right-continuous and $\{0 < S(t) < 1\} \subset J_X = \{0 < S_X(t) < 1\}$. Since K and Kh are both right-continuous, h is right-continuous on J_X by (2.15). Since $Kh \in D_0[a, b]$, $h(t) = 0$ for $t \notin J_X$. It remains to show that the set $J_X \cap \{t : S_Y(t) \leq S_Z(t -)\}$ does not have a limit point from left. If $S_Y(t) \leq S_Z(t -)$ and $0 < S_X(t) < 1$, then by (2.6) $0 \leq S_Y(u) - S_Z(u) \leq S_Z(t -) - S_Z(u)$ for $u \geq t$ and $S_Z(t -) > S_Z(t + \varepsilon)$ for $\varepsilon > 0$, so that

$$\begin{aligned} & - \int_{t \leq u < t+\varepsilon} [S_Y(u) - S_Z(u)]^{-1} dS_Z(u) \\ & \geq - \int_{t \leq u < t+\varepsilon} [S_Z(t -) - S_Z(u)]^{-1} dS_Z(u) \geq 1, \quad \forall \varepsilon > 0. \end{aligned}$$

It follows from (2.13) that the set $\{S_Y(t) \leq S_Z(t -), 0 < S_X(t) \leq \tau\}$ is finite for all $0 < \tau < 1$.

STEP 4 (Conclusion). Let us consider the case $\|K_m h_m\| \leq 1$ first. If Kh is a cluster point of the sequence $K_m h_m$, then by the conditions of this lemma and (2.15) we have $R_S h = g$. Since $K_m h_m = g_m + v_m^+ + v_m^-$ and $\|g_m - g\| \rightarrow 0$, Steps 1 and 2 imply that the sequence $K_m h_m$ is totally bounded. By Step 3, the sequence has only one cluster point. Hence $\|K_m h_m - Kh\| \rightarrow 0$

and $R_S h = g$. if $\sup_m \|K_m h_m\| = M < \infty$, then the conditions of this lemma hold for h_m/M and g_m/M , and we come back to the case $\|K_m h_m\| \leq 1$. The proof is completed if we can find a contradiction to the case where $\|K_{m_k} h_{m_k}\| = M_k \rightarrow \infty$. Let $h'_k = h_{m_k}/M_k$, $g'_k = g_{m_k}/M_k$, $S'_{X,k} = S_{X,m_k}$, $S'_{Y,k} = S_{Y,m_k}$ and $S'_{Z,k} = S_{Z,m_k}$. Then by Lemma 2 for the case $\|K_m h_m\| \leq 1$, we have $\|K'_k h'_k\| \rightarrow 0$, since $\|g'_k\| \rightarrow 0$. This is a contradiction to $\|K'_k h'_k\| = 1$. $\square$

REFERENCES

- AYER, M., BRUNK, H. D., EWING, G. M., REID, W. T. and SILVERMAN, E. (1955). An empirical distribution function for sampling with incomplete information. *Ann. Math. Statist.* **26** 641–647.
- BERAN, R. (1977). Estimating a distribution function. *Ann. Statist.* **5** 400–404.
- BRESLOW, N. and CROWLEY, J. (1974). A large sample study of the life table and product limit estimates under random censorship. *Ann. Statist.* **2** 437–453.
- CHANG, M. N. (1990). Weak convergence of a self-consistent estimator of the survival function with doubly censored data. *Ann. Statist.* **18** 391–404.
- CHANG, M. N. and YANG, G. L. (1987). Strong consistency of a nonparametric estimator of the survival function with doubly censored data. *Ann. Statist.* **15** 1536–1547.
- COX, D. R. and OAKES, D. (1984). *Analysis of Survival Data*. Chapman and Hall, New York.
- EFRON, B. (1967). The two-sample problem with censored data. *Proc. Fifth Berkeley Symp. Math. Statist. Probab.* **4** 831–854. Univ. California Press, Berkeley.
- GILL, R. D. (1983). Large sample behaviour of the product-limit estimator on the whole line. *Ann. Statist.* **11** 49–58.
- GILL, R. D. (1989). Non- and semi-parametric maximum likelihood estimators and the von Mises method (part I). *Scand. J. Statist.* **16** 97–128.
- GROENEBOOM, P. (1987). Asymptotics for incomplete censored observations. Technical Report 87-18, Dept. Mathematics, Univ. Amsterdam.
- KAPLAN, E. L. and MEIER, P. (1958). Nonparametric estimation from incomplete observations. *J. Amer. Statist. Assoc.* **53** 457–481.
- LAGAKOS, S. W., BARRAJ, L. M. and DE GRUTTOLA, V. (1988). Nonparametric analysis of truncated survival data with applications to AIDS. *Biometrika* **75** 515–523.
- LINDEN-BELL, D. (1971). A method of allowing for known observational selection in small samples applied to 3CR quasars. *Monthly Notices Roy. Astronom. Soc.* **155** 95–118.
- POLLARD, D. (1984). *Convergence of Stochastic Processes*. Springer, New York.
- SAMUELSON, S. O. (1989). Asymptotic theory for non-parametric estimators from doubly censored data. *Scand. J. Statist.* **16** 1–21.
- TSAI, W. Y. and CROWLEY, J. (1985). A large sample study of generalized maximum likelihood estimators from incomplete data via self-consistency. *Ann. Statist.* **13** 1317–1334.
- TURNBULL, B. W. (1974). Nonparametric estimation of a survivorship function with doubly censored data. *J. Amer. Statist. Assoc.* **69** 169–173.
- WELLNER, J. A. (1982). Asymptotic optimality of the product limit estimator. *Ann. Statist.* **10** 595–602.
- WOODROOFE, M. (1985). Estimating a distribution function with truncated data. *Ann. Statist.* **13** 163–177.

DEPARTMENT OF MATHEMATICS AND STATISTICS
MCGILL UNIVERSITY
805 SHERBROOKE ST. WEST
MONTREAL, QUEBEC H3A 2K6
CANADA

DEPARTMENT OF STATISTICS
RUTGERS UNIVERSITY
HILL CENTER
BUSCH CAMPUS
NEW BRUNSWICK, NEW JERSEY 08903