The rate of ESRD has increased steadily in the United States over the past three decades. Insights into the epidemiology and treatment of ESRD have emerged from many investigations including those conducted by the United States Renal Disease System. Much less is known about the epidemiology of pre-ESRD chronic renal insufficiency (CRI), especially the relationship between CRI and cardiovascular disease (CVD).

CRI has been recognized as a silent epidemic (1) affecting more than ten million Americans. The burden of morbidity and mortality from CRI derives from the progression of CRI to ESRD and the disproportionate risk of CVD in the setting of CRI. CRI is strongly and independently associated with CVD, even after adjustment for traditional CVD risk factors. These findings led to the hypothesis that specific “uremia-related risk factors” augment the rate of CVD (2) and cause many patients with CRI to succumb to fatal cardiovascular events before needing renal replacement therapy.

The National Institute of Diabetes, Digestive, and Kidney Diseases (NIDDK) established the Chronic Renal Insufficiency Cohort (CRIC) Study in 2001 to improve understanding of the relationship between CRI and CVD. The CRIC Study goals are to examine risk factors for progression of CRI and CVD among patients with CRI and develop predictive models to identify high-risk subgroups, informing future treatment trials and increasing application of available preventive therapies. Improved recognition of etiological factors will permit development of interventions to reduce the burden of advanced renal failure and cardiovascular morbidity and mortality. The CRIC Study will address five principal hypotheses:

1. A set of nontraditional risk factors is associated with both progression of CRI and development of ESRD. (Nontraditional risk factors indicate factors that have not yet been well studied in renal disease in contrast to well studied factors such as BP and proteinuria.)
2. A set of nontraditional risk factors is associated with subclinical measures of CVD progression and clinical events, and measures of CVD progression in the setting of CRI.
3. Risk factors for CRI progression and CVD in the setting of CRI vary by demographic characteristics and the presence of diabetes mellitus.
5. Progression of CRI as estimated by serum creatinine and currently available serum creatinine-based formulae yield biased estimates of the rate of progression of CRI.

Materials and Methods

Study Organization

The CRIC Study consists of a Scientific and Data Coordinating Center (SDCC), in Philadelphia, Pennsylvania; seven clinical centers (Ann Arbor, Michigan; Baltimore, Maryland; Chicago, Illinois; Cleveland, Ohio; New Orleans, Louisiana; Philadelphia, Pennsylvania; and Oakland, California); central laboratories for analysis of GFR and biochemistries; three central reading centers (coronary calcium measurement, echocardiography, and electrocardiography); a Scientific Advisory Committee; and NIDDK project scientists.

Study Design

Each clinical center will enroll approximately 430 to 500 individuals over a 33-mo period to establish a cohort of 3000 participants. Participants will be followed until death or dropout from the study. Follow-up will continue even after ESRD occurs.

Cohort Participants

The CRIC Study will include a racially and ethnically diverse group of adults with a broad spectrum of renal disease severity, half of whom will have diagnosed diabetes mellitus, the remainder having a broad array of nondiabetic renal disease.

Patients aged 21 to 74 yr with CRI will be enrolled in the CRIC Study. The upper age limit of 74 yr ensures the ability to evaluate a broad array of nondiabetic renal disease.

Follow-Up and Retention

Recruitment

Subject recruitment will vary by clinical center. The recruitment goal of 3000 requires approximately 450 participants from each clinical center (including replacement of dropouts during the first year, anticipated to be as high as 5%) (5,6). Most clinical centers can access at least one large database to identify individuals with elevated serum creatinine levels. Recruitment also will occur at clinics enriched with cases of CRI. Securing local physician approval and contacting potential screenees depend on local institutional review boards’ guidelines and the requirements of each medical facility.

Screening and Enrollment

Eligible persons will be evaluated at baseline when detailed socio-demographic information, medical and family history, medications used in the previous 30 d, anthropometric measures (weight, height, midabdominal circumference), resting BP, heart rate, physical evidence of peripheral vascular disease, and ankle-brachial index will be collected. In addition, blood specimens will be obtained, and a 24-h urine sample collection will be initiated. 125I-iothalamate clearances will be scheduled for one-third of all participants. Questionnaires concerning quality of life, dietary assessment, physical activity, health behaviors, depressive symptoms, cognitive function, and health care resource utilization will also be administered.

Follow-Up and Retention

Retention strategies that should enhance the attractiveness of long-term participation include free medical testing, frequent contact with participants via personalized mailings, telephone calls, newsletters

Table 1. Anticipated race ethnic target distribution in CRIC Study

<table>
<thead>
<tr>
<th>Race/Ethnic Group</th>
<th>Final Proportion of CRIC (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Caucasian</td>
<td>50</td>
</tr>
<tr>
<td>African American/Black</td>
<td>40</td>
</tr>
<tr>
<td>Latino/Hispanic, Asian/Pacific Islander, and other</td>
<td>10</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Age stratum</th>
<th>Eligible Estimated GFR Range (ml/min 1.73 m²)</th>
<th>No diabetes (%)</th>
<th>Diabetes (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>21 to 44 yr</td>
<td>20 to 70</td>
<td>12.5</td>
<td>12.5</td>
</tr>
<tr>
<td>45 to 64 yr</td>
<td>20 to 60</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>65 to 74 yr</td>
<td>20 to 50</td>
<td>12.5</td>
<td>12.5</td>
</tr>
</tbody>
</table>

* Based on simplified MDRD equation (3).
and educational sessions, and reimbursement of time and travel expenses.

Participants will return annually for in-person follow-up visits. Participants will be contacted by telephone at the 6-mo interval between clinic visits and queried about study outcomes and updates on general health and contact information. Newsletters and information regarding CRI and CVD will supplement in-person and telephone contacts. Consistent with other cohort studies (e.g., Atherosclerosis Risk in Communities Study, Cardiovascular Health Study) up to 3 to 5% of participants may be lost to follow-up annually. Persistent efforts will be made to prevent participant dropout. The National Death Index will be searched periodically for all participants lost-to-follow-up to ensure complete vital status information.

Collection of Study Data

Plasma and urine samples will be collected annually and stored. These specimens will enable exploration of biomarkers for lipid metabolism, inflammation, coagulation status, oxidative stress, endothelial function, among others, as predictors of the progression of CRI and CVD. Blood samples will also be collected to extract DNA for future genetic studies.

Study Outcomes: Renal

The primary renal outcome is progression of CRI defined by reduction in estimated GFR. Renal events are defined as the need for renal replacement therapy (ESRD), an estimated halving of GFR, and/or a 25 ml/min per 1.73 m² decline in GFR from baseline. In the whole cohort, estimated GFR is based on the MDRD formula which relies on serum creatinine, pending development of a GFR estimating equation derived from CRIC Study data (3). This equation will be developed among the 125I-iothalamate subcohort, based on serum creatinine as well as other biologic measures (e.g., serum albumin, serum cystatin C, measures or estimates of body composition) and clinical characteristics (e.g., age, gender, race, and diabetes status). Iothalamate-based clearance measurements are needed because of certain gaps in our knowledge of the accuracy of estimating equations that allow for the estimation of individual participants at different times on the rate of failure using weighted estimation of slopes and intercepts, and for comparison of subgroups defined at baseline and over time. Analytical approaches will account for non-independence of repeated measurements from individual participants and missing data (15,16).

Analysis of repeated measures (e.g., GFR) will use standard mixed effects growth curve models supplemented by generalized estimating equations that allow for the estimation of individual participants’ slopes and intercepts, and for comparison of subgroups defined at baseline and over time. Analytical approaches will account for non-independence of repeated measurements from individual participants and missing data (15,16).

Statistical Considerations

Research questions will be analyzed separately in diabetic and non-diabetic participants and overall, unless there is statistical evidence of interaction by diabetes status or a strong biologic evidence for an interaction. Failure-time, repeated measures, and nested analyses will be the principal analytical approaches. Several main study endpoints are failure-times: CVD events and clinically important reductions in renal function (e.g., ESRD and/or significant declines in estimated GFR). Kaplan Meier curves and Cox proportional hazards analysis will be the principal statistical approaches using standard procedures to assess underlying assumptions and adequacy of fit of multivariable models (10–12). Proportional hazards analysis also will be used to explore the joint effects of treatments or exposures received at different times on the rate of failure using weighted estimation of marginal structural models (13) and G-estimation of structural nested models (14).

Analysis of repeated measures (e.g., GFR) will use standard mixed effects growth curve models supplemented by generalized estimating equations that allow for the estimation of individual participants’ slopes and intercepts, and for comparison of subgroups defined at baseline and over time. Analytical approaches will account for non-independence of repeated measurements from individual participants and missing data (15,16).

Statistical methods will accommodate staggered entry and different lengths of follow-up among subgroups, and permit evaluation of bias introduced by differential follow-up. Characteristics of participants without complete follow-up will be examined and factors associated with drop-out will be modeled.

Analyses of selected biomarkers, 125I-iothalamate clearance, and coronary calcification, collected or analyzed only on a random subset of participants will resemble those of other repeated measures. For these analyses, multiple imputation (17) also will be considered for dealing with missing data on variables in participants not in the subcohort.

Event-based analyses will supplement analyses of GFR as a continuous, repeated outcome measure. Participants will be considered to have failed if they either develop ESRD or experience a substantial decrease in GFR. These analyses will supplement the primary analysis examining change in equation-based estimated GFR criterion as a substitute for the directly measured 125I-iothalamate clearance criterion; the estimates will derive from GFR prediction equations developed using study data.

Certain biomarkers will be available from all participants by analyzing blood samples that are stored and frozen at annual visits. Analysis of these data to look at the associations of predictor variables and outcomes will use the case-cohort approach of Prentice (18) that permits estimation of relative hazards. The efficiency of this approach can be improved by weighting methods that can allow inclusion in the...
analysis of participants who do not develop the outcome of interest (19).

**Statistical Power**

The CRIC Study will have ample statistical power for time-to-event and repeated measures analyses. For a sample size of 1500, the size of the diabetic and nondiabetic subgroups, an exposure prevalence of 0.1 and 0.5, the CRIC study will have 80% power to detect a hazard ratio of approximately 1.80 and 1.60, respectively. Analogously, the study will have 80% power to detect a difference in slope of change in GFR of 0.6 and 0.4 ml/min.

**Discussion**

The NIDDK developed the CRIC Study in response to the epidemic of CRI and the acknowledgment that existing studies of CRI and ESRD provide an incomplete understanding of the burden of CRI. Morbidity and mortality associated with CRI, often from CVD, make the long-term study of afflicted individuals compelling because in certain individuals CRI may not progress to ESRD, or because mortality from competing illness, typically, CVD occurs.

The CRIC Study represents a major commitment to use observational epidemiology to address research questions regarding etiology, prognosis, therapy, health services utilization, and quality of life among patients with both diabetic and nondiabetic CRI. In the CRIC Study, analogous to the Framingham Heart and the ARIC studies, the NIDDK has established a unique resource that will explore long-term consequences of CRI, as well as suggest novel mechanistic hypotheses. Providing a clinical laboratory for this disease which progresses in a variable, but often protracted time-frame will enable such goals.

Until now, most follow-up data on CRI have come from clinical trials of patients with CRI and from large-scale cohort studies conducted in which CRI was not a primary focus. Although selective enrollment and limited scope of risk factor data narrow the extent of inferences from these studies, data from these studies complement the CRIC Study.

In the Hypertension, Detection, and Follow-up Program (HDFP), baseline serum creatinine >1.7 mg/dl was associated with a 2.2-fold higher adjusted odds of death at 8 yr compared with baseline serum creatinines <1.7 mg/dl (20). Consistent with these findings, the Cardiovascular Health Study reported an adjusted mortality rate 71% higher among 5000 participants with baseline serum creatinine ≥1.5 mg/dl (21). Both small amounts of proteinuria and elevated creatinine have independently been associated with increased CV mortality in a representative sample of the general population (22).

Other studies have indicated the extent to which the increase in the rate of death in the setting of CRI is due to CVD. Jungers et al. (23) observed a two- to threefold higher rate of MI among 147 patients with CRI compared with the incidence in the French general population. CV events were independently associated with tobacco use, hypertension, elevated fibrinogen and homocysteine, and low HDL cholesterol. Secondary analyses of the MDRD study demonstrated the large burden of CVD in the setting of CRI, finding that 25% of first hospitalizations were for CVD (24). Two trials of angiotensin converting enzyme inhibitors in nondiabetic CRI provided data on the rate of the combined endpoint of sudden death and MI. Among patients with a serum creatinine between 1.5 and 4.0 mg/dl, there was a rate of 1% per year with the use of benazepril (25), similar to that observed among patients with >3 g/d proteinuria enrolled in the REIN Study (26).

More recently, Culleton et al. (27) reported on 6233 adults in the Framingham Heart Study. The rate of all-cause mortality and CVD was compared between participants with normal and mild CRI (serum creatinine ≥136 umol/L in men and ≥120 umol/L in women). The adjusted rate ratios for all cause mortality were 1.31 (95% CI: 1.02 to 1.67) for men and 1.08 (95% CI: 0.87 to 1.34) for women. The adjusted rate ratios for CVD were 1.06, 95% CI (0.79 to 1.43) for men, and 1.04, 95% CI (0.79 to 1.37) for women. These studies provided compelling evidence for the morbidity risks of CRI beyond simple progression to ESRD. However, full understanding of the relationship between CRI and CVD awaits research that examines biomarkers of putative mechanistic pathways and uses more sensitive tools to detect CVD such as EBCT or echocardiography.

Concurrent with CRIC are at least four longitudinal studies that are exploring risk factors for progression of CRI. The National Health and Nutrition Examination Survey (NHANES) collects data on the prevalence of nephrologic conditions in the US population, and the association between kidney disease and diseases including diabetes and hypertension, and monitors kidney disease prevalence and risk factors over time. The African American Study of Kidney Disease (AASK) Cohort Study investigates environmental, socioeconomic, genetic, physiologic, and other comorbid factors that influence progression of kidney disease in a cohort of African Americans with hypertensive kidney disease. KEEP 3.0, a longitudinal cohort study supported by the National Kidney Foundation, will begin in 2003, and will enroll 6900 participants at risk for kidney disease from 15 sites. KEEP 3.0 participants will be followed over 3 yr to evaluate progression of kidney disease and the effect of provider and participant educational interventions on disease progression. The planned Canadian Prevention of Renal and Vascular Events Trial in Chronic Renal Disease (CAN-PREVENT) is a randomized clinical trial of intensive cardiovascular risk factor interventions compared with usual care in Canadian patients with moderate CRI. In all instances, the CRIC Study will extend or expand on these studies with respect to types of renal disease and mechanistic pathways under study, and use of state-of-the-art tools to track the progression of CRI and CVD.

Interventional studies designed to prevent the progression of CRI can only occur after gaining sufficient knowledge of the burden of disease, its natural history, and its putative mechanisms. CRIC will provide important information on potential risk factors for progressive CRI and CVD as did studies of the relationship between cholesterol and hypertension to CVD before treatment trials of lipid- and BP-lowering drugs. CRIC should provide this knowledge, allowing formulation of hypotheses regarding therapy that will serve as the basis for
targeted interventional trials focused on reducing the burden of CRI and CVD.

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