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# Albuminuria trajectories following intensive lifestyle intervention with or without bariatric surgery in adolescents with and at risk of type 2 diabetes

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ABSTRACT

*Aim:* Albuminuria reflects early renal injury and may precede type 2 diabetes, particularly among Māori and Pacific adolescents in New Zealand who experience a high burden of severe obesity. Evidence for renal benefits of bariatric surgery in adolescents is limited. We examined the effect of intensive lifestyle intervention, with or without bariatric surgery, on urine albumin-creatinine ratio (UACR).

*Methods:* Adolescents aged 15–17 years with BMI $\geq$ 35 kg/m$^2$ completed a 12-week very-low-calorie diet (VLCD) programme. Screening HbA1c identified prediabetes or type 2 diabetes, and eligible participants were offered bariatric surgery. UACR was measured at up to 14 time points over 36 months. Longitudinal mixed-effects models assessed trajectories of log-UACR, adjusting for time, surgery status, and weight change, with participant-level random intercepts.

*Results:* Twenty adolescents (11 female; 19 Māori or Pacific; 8 prediabetes and 9 type-2 diabetes) were enrolled; seven underwent surgery. Over follow-up (6–36 months), a significant time $\times$ surgery interaction was observed ($p < 0.001$). At 36-months, surgical participants had an 86 (95% CI 72–92)%, reduction in UACR, whereas non-surgical participants showed no significant change (+2; 95% CI − 7 to + 12)%.

*Conclusions:* Bariatric surgery combined with lifestyle intervention was associated with sustained reductions in albuminuria, suggesting a potential renoprotective effect in high-risk adolescents.

## 1. Introduction

Diabetic kidney disease (DKD) is emerging earlier in life, mirroring the increasing prevalence of type 2 diabetes among adolescents and young adults [1]. Youth-onset type 2 diabetes is characterised by a more aggressive course than adult-onset disease, with faster progression to albuminuria, chronic kidney disease (CKD), and other vascular complications [2,3]. Adolescent obesity, a global health crisis that has risen sharply over recent decades, is a key driver of this risk [4].

Importantly, obesity itself can directly injure the kidney independent of diabetes. Obesity-related glomerulopathy (ORG) is characterised by glomerular hyperfiltration, increased intraglomerular pressure, and secondary focal segmental glomerulosclerosis, leading to albuminuria even in the absence of hyperglycaemia [5,6]. ORG has been increasingly recognised in both adult and paediatric populations and is associated with early, potentially reversible renal injury [5,7]. Observational and interventional studies demonstrate that weight reduction, achieved through lifestyle therapy or bariatric surgery, can reduce proteinuria, improve hyperfiltration, and stabilise renal function [8–11], suggesting that obesity-driven kidney injury may be modifiable.

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Excess weight in youth is strongly linked to early-onset type 2 diabetes, cardiovascular disease, and renal dysfunction [12,13]. Amongst markers of early renal injury, the urine albumin-creatinine ratio (UACR) is widely used and is predictive of future CKD [14].

In New Zealand, obesity remains a major health concern, disproportionately affecting disadvantaged communities. The South Auckland region, one of the country's most ethnically diverse and socioeconomically challenged districts, reports some of the highest prevalence of adolescent obesity nationwide [15]. These disparities are particularly striking amongst Māori and Pacific youth, who face a higher burden of obesity-related complications, including insulin resistance, dyslipidaemia, and early renal injury [16,17]. Structural disparities in access to nutritious food and physical activity opportunities further compound these risks [18].

Although lifestyle/dietary interventions, including Very Low-Calorie Diets (VLCDs), can promote weight loss and metabolic improvement in adolescents [19], their long-term efficacy is variable. Recent evidence indicates glucagon-like peptide-1 (GLP-1) receptor agonists can produce clinically meaningful weight reduction in adolescents with severe obesity, yet their durability and long-term impact on metabolic or renal outcomes remain uncertain [20]. Bariatric surgery, proven effective in adults with severe obesity, is increasingly considered in adolescent populations [21]. However, evidence regarding its safety and long-term benefits remain limited [22], particularly in Māori and Pacific populations who face unique developmental and access challenges [23].

One area of particular interest is how obesity and its treatment influence renal function in adolescents, especially those with or at high risk of type 2 diabetes. Despite growing use of GLP-1 receptor agonists and bariatric surgery in youth, little is known about their effects on early kidney injury or complication risk [24] – particularly among Polynesian, Indigenous and other high-risk populations. While the UACR is an established marker of early renal and cardiometabolic injury [14], limited data exist on how intensive weight-loss interventions, including bariatric surgery, influence UACR trajectories in adolescents with or at risk of type 2 diabetes.

This study aims to address this evidence gap by evaluating the effect of a structured weight-loss programme, with or without bariatric surgery, on UACR in adolescents with morbid obesity.

## 2. Methods

### 2.1. Study design and participants

This prospective cohort study was conducted in the Counties Manukau region of New Zealand. Adolescents aged 15 years and 9 months to 18 years with morbid obesity (BMI $\geq$ 35 kg/m$^2$), at high risk for type 2 diabetes and associated comorbidities, were eligible to participate. Exclusion criteria included type 1 diabetes, previous bariatric surgery, secondary causes of obesity, active psychiatric illness, or medical contraindications to the VLCD or bariatric surgery. Eligible participants, along with their parents or legal guardians, provided written informed consent prior to any study-specific procedures. The study was approved by the New Zealand Health and Disability Ethics Committee (reference number: 19/NTB/21/AM02). The study aimed to assess the effects of a structured weight-loss programme and bariatric surgery on metabolic and renal outcomes in this population.

### 2.2. Screening and baseline assessment

After written informed consent, participants underwent screening for pre-diabetes or type 2 diabetes using glycated haemoglobin ($HbA_{1c}$) testing. Baseline assessments included anthropometry (height, weight, BMI), blood pressure, laboratory measurements (UACR, liver function enzymes (alkaline phosphatase [ALP], gamma-glutamyl transferase [GGT], alanine aminotransferase [ALT]), and fasting C-peptide concentrations.

Blood samples (non-fasting venous) and first-morning urine samples were collected at each assessment point and analysed for UACR. In keeping with the pragmatic design of the study and routine clinical workflow, UACR was determined from a single early-morning specimen rather than the mean of repeated samples. While repeated collections are often recommended in controlled trials to reduce intra-individual variability, systematic duplicate sampling was not feasible within this real-world adolescent programme. Estimated glomerular filtration rate (eGFR) was calculated using age-appropriate equations, and glomerular hyperfiltration was defined as eGFR $>$ 130 mL/min/1.73 m$^2$, consistent with published thresholds in paediatric and adolescent populations [25]. UACR was determined from the first-morning spot urine using an immunoturbidimetric assay for albumin and an enzymatic colorimetric method for creatinine. HbA1c was analysed using an NGSP-certified HPLC method, and C-peptide concentrations were measured by chemiluminescent immunoassay as an index of endogenous insulin secretion. Liver enzymes (ALP, GGT, ALT) were measured on an automated biochemistry analyser.

Cultural support was embedded throughout the study, with Māori and Pacific research staff and liaison personnel ensuring culturally responsive engagement and addressing the specific needs of participants and families.

### 2.3. Intervention: Very Low-Calorie diet and support services

All participants commenced a 12-week structured weight-loss programme incorporating the Optifast® VLCD, providing approximately 800 kcal per day, with balanced macronutrient distribution. Throughout this phase, participants received multidisciplinary support, including psychological assessment, dietetic counselling, cultural liaison, and family-based behavioural support. Psychological support was arranged and encouraged if required. This phase emphasised both weight reduction and the adoption of healthy lifestyle habits. The VLCD also served as part of the standard pre-operative preparation for bariatric surgery at this centre, including facilitation of hepatic volume reduction. However, weight loss achieved during the VLCD was not used as the sole determinant of progression to surgery.

Adherence to the VLCD was supported through regular clinical follow-up and dietetic review as part of routine care. This included discussion of dietary intake and reinforcement of adherence at scheduled visits. However, formal quantitative measures of compliance (e.g., structured food diary analysis or adherence scoring) were not systematically collected, and therefore comparisons of adherence between groups were not undertaken.

### 2.4. Bariatric surgical pathway

At completion of the 12-week VLCD, participants were reassessed for bariatric surgery (VLCD + Surgery) eligibility through a multidisciplinary evaluation addressing clinical criteria, psychosocial readiness, family support, and engagement in the weight-loss programme. Criteria for the surgery included: (1) be aged $\geq$ 16 years, (2) demonstrated weight loss from baseline, (3) provision of written informed consent, and (4) absence of surgical contraindications as determined by the multidisciplinary surgical team.

Progression to surgery was determined through multidisciplinary evaluation rather than weight loss alone. In addition to meeting clinical criteria, participants were required to have a BMI $<$ 60 kg/m$^2$ and undergo assessment of psychological readiness and overall suitability for surgery, including review by Psychological Medicine, consistent with standard clinical practice at the study site. Eligible participants underwent laparoscopic sleeve gastrectomy, the sole surgical method used in this study, performed by an experienced bariatric surgical team at a tertiary referral hospital, following established perioperative protocols.

The study was conducted during the COVID-19 pandemic, during which elective surgical services were suspended. This resulted in longer-

than-usual intervals between completion of the VLCD and surgery for some participants. During this period, participants continued to receive lifestyle intervention, counselling, and clinical follow-up, and were expected to maintain their weight loss prior to surgery. While adherence to the VLCD was supported through regular clinical and dietetic follow-up, formal quantitative measures of compliance (e.g., food diaries) were not systematically recorded.

### 2.5. Comparison group and Follow-Up

Participants who were ineligible for, or declined surgery, comprised the comparison group (VLCD Only) and continued with the intensive lifestyle intervention and weight maintenance support. This programme comprised ongoing dietetic review, behavioural counselling, structured physical activity guidance, and regular clinical follow-up, as detailed in Sections 2.3 and 2.6. Recruitment continued until 21 participants (VLCD Only and VLCD + Surgery) were enrolled.

Participants continued to receive standard clinical care for diabetes and metabolic comorbidities throughout the study period, including adjustment of conventional therapies such as metformin and insulin as clinically indicated. GLP-1 receptor agonists and dual GLP-1/GIP agonists were not used during the study period. Although liraglutide was available in New Zealand at the time, it was not registered for use in individuals aged 12–18 years and was therefore not prescribed in this cohort. Changes in other anti-diabetes therapies were not systematically captured as part of the study protocol.

All participants were followed for a minimum of seven months post-surgery, with repeated evaluations conducted at scheduled intervals across the three-year study period. At each follow-up visit, the same clinical and biochemical assessments described at baseline, including renal (UACR, eGFR), hepatic (ALT, GGT, ALP), metabolic (HbA1c, C-peptide), and lipid (total, HDL, LDL cholesterol, triglycerides) parameters, were reassessed to monitor longitudinal change. These longitudinal data were used to compare the effects of VLCD + Surgery versus VLCD Only, on renal and hepatic function, metabolic trajectories, and to explore potential cardiometabolic benefits over time.

### 2.6. Group education and behavioural support

Participants and their families attended primarily individual sessions designed to reinforce lifestyle behaviours, nutrition education, and physical activity. Beginning at month 3 (weight-maintenance phase), sessions emphasised activity planning, motivation, overcoming barriers, and practical approaches for integration exercise into daily routines. Participants were also introduced to home-based resistance and stretching exercises, practiced in supervised sessions and reinforced with written educational materials.

### 2.7. Statistical analysis

Descriptive statistics were used to summarise baseline participant characteristics. Continuous variables reported as means (± standard deviation) or medians (interquartile range), and categorical variables as frequencies (percentages). Weight change from baseline to 12 weeks was expressed as both absolute (kg) and percent (%) change. For participants missing weight at 12 weeks, the last available observation (e.g., 8 weeks) was carried forward (LOCF). Given the small sample size and skewed distributions, the Wilcoxon signed-rank test was used as the primary nonparametric test for paired comparisons, with paired t-tests provided as supportive analyses.

For renal outcomes, both UACR and eGFR were analysed longitudinally. Extreme outliers were adjusted using a modified Winsoring procedure, in which values below the 1st and above the 99th percentiles were replaced with the corresponding percentile cut point. This approach minimised the influence of extreme observations while preserving the full sample size.

Longitudinal changes in log-transformed UACR and eGFR were examined using mixed-effects linear regression models. Fixed effects included timepoint, surgery status, and their interaction, with random intercepts specified to account for within-participant correlation across repeated measures. Parallel models were fitted for eGFR to assess renal function trajectories over time. Sensitivity analyses were performed using both complete-case and multiple-imputed datasets, yielding comparable results.

To explore whether changes in albuminuria were weight-dependent and/or related to glycaemic status, additional mixed-effects models of log(UACR) included baseline weight and time-varying percent change in HbA1c. These analyses were considered exploratory and intended to assess whether the observed UACR trajectories by intervention group persisted after accounting for these factors.

Statistical significance was defined as a two-sided $\alpha = 0.05$. All analyses were performed using SAS version 9.4 (SAS Institute, Cary, NC).

### 2.8. Data statement

The datasets generated during and/or analysed during the current study are not publicly available due to the small number of participants and potential for identification but are available from the corresponding author upon reasonable request.

## 3. Results

### 3.1. Participant characteristics

A total of 21 adolescents with morbid obesity (12 females, 9 males; aged 15–17 years) were enrolled and completed the 12-week VLCD intervention. One participant was withdrawn following a diagnosis of type 1 diabetes at baseline. Of the 20 participants, nineteen identified as Māori or Pacific (95%), and one participant (5%) identified as New Zealand European. At baseline, 9 (45.0%) had type 2 diabetes, 8 (40.0%) had pre-diabetes, and 3 (15.0%) had no evidence of dysglycaemia using HbA1c. Mean eGFR was 144.3 ± 17.0 mL/min/1.73 $m^2$, with no significant difference between groups (142.9 ± 13.5 mL/min/1.73 $m^2$ in the VLCD + Surgery group vs 145.0 ± 19.1 mL/min/1.73 $m^2$ in the VLCD Only group; $p = 0.575$). No participant demonstrated evidence of impaired kidney function, defined as an eGFR < 90 mL/min/1.73 $m^2$, at enrolment, but 16 (80%) exhibited glomerular hyperfiltration, defined as an eGFR of ≥ 130 mL/min/1.73 $m^2$. After reassessment for surgical eligibility, 7 participants (4 females, 3 males) underwent laparoscopic sleeve gastrectomy (VLCD + Surgery), while the remaining 13 continued with lifestyle intervention and weight-maintenance programme and served as the comparison group (VLCD Only) (Table 1).

### 3.2. Impact of VLCD on weight, UACR, and eGFR

At baseline, the mean weight was 150.9 ± 47.7 kg, which decreased to 144.6 ± 46.4 kg after 12-weeks on the VLCD. The mean absolute weight reduction was −6.2 ± 6.6 kg, corresponding to a median percent weight change of −3.4% (IQR: −6.9% to −1.5%). Statistical testing confirmed that participants experienced significant weight loss over the initial 12-week VLCD phase, with consistent results across parametric ($p < 0.001$) and nonparametric ($p < 0.001$) methods.

During the initial 12-week VLCD intervention, no significant change in log-transformed UACR was observed (Wilcoxon signed-rank $p = 0.945$; paired $t$-test $p = 0.987$). Back-transformed estimates confirmed that the geometric mean UACR remained unchanged, from 5.6 mg/mmol (95% CI: 2.4–13.1) at baseline to 4.8 mg/mmol (95% CI: 2.1–11.1). Similarly, no significant change in eGFR was observed over the VLCD phase (baseline: 144.3 ± 17.0 vs. 12-week: 144.6 ± 16.7 mL/min/1.73 $m^2$; $p = 0.877$).

**Table 1**
Baseline characteristics of adolescents enrolled in the VLCD intervention study.

| Characteristic | Overall (N = 20) | VLCD + Surgery (n = 7) | VLCD Only (n = 13) | *p* |
|---|---|---|---|---|
| Age at Consent, Years | 16.4 ± 1.0 | 16.7 ± 1.1 | 16.2 ± 1.0 | 0.378 |
| Gender: Female | 11 (55.0) | 4 (57.1) | 7 (53.9) | 0.888 |
| Ethnicity | | | | |
| New Zealand Europeans | 1 (5.0) | 1 (14.3) | 0 | 0.436 |
| Tongan | 9 (45.0) | 2 (28.6) | 7 (53.9) | |
| Samoan | 8 (40.0) | 3 (42.9) | 5 (38.5) | |
| Māori | 2 (10.0) | 1 (14.3) | 1 (7.7) | |
| Diabetes Diagnosis | | | | |
| None | 3 (15.0) | 2 (28.6) | 1 (7.7) | 0.431 |
| Pre-Diabetes | 8 (40.0) | 2 (28.6) | 6 (46.2) | |
| Type 2 Diabetes | 9 (45.0) | 3 (42.9) | 6 (46.2) | |
| Weight, kg | 150.9 ± 47.7 | 146.8 ± 28.9 | 153.0 ± 56.2 | 0.877 |
| Body Mass Index, kg/m$^2$ | 50.2 ± 14.2 | 49.2 ± 7.6 | 50.7 ± 17.0 | 0.656 |
| HbA1c, % | 7.7 ± 2.4 | 8.1 ± 2.9 | 7.5 ± 2.2 | 0.923 |
| HbA1c, mmol/mol | 60.6 ± 26.2 | 64.7 ± 32.0 | 58.4 ± 23.7 | 0.923 |
| Urate, mmol/L | 0.4 ± 0.1 | 0.3 ± 0.1 | 0.4 ± 0.1 | 0.265 |
| eGFR, mL/min/1.73 m$^2$ | 144.3 ± 17.0 | 142.9 ± 13.5 | 145.0 ± 19.1 | 0.575 |
| Hyperfiltration (> 130) | 16 (80.0) | 6 (85.7) | 10 (76.9) | 0.381 |
| UACR, mg/mol | 2.2 [0.0–7.1] | 4.6 [0.0–23.2] | 1.9 [0.0–4.9] | 0.630 |
| C-peptide, pmol/L | 1351 [1095.0–2458.0] | 1321 [1118.0–2458.0] | 1416 [919.5–2382.5] | 0.902 |
| Insulin, mU/L | 34.2 [17.9–91.0] | 34.2 [18.9–133.0] | 32.1 [17.8–89.5] | 0.902 |
| Lipids, mmol/l | | | | |
| Total Cholesterol | 4.3 ± 0.6 | 4.3 ± 0.7 | 4.3 ± 0.6 | 0.893 |
| HDL | 1.1 ± 0.2 | 1.1 ± 0.3 | 1.1 ± 0.2 | 0.832 |
| LDL | 2.4 ± 0.6 | 2.1 ± 0.8 | 2.5 ± 0.5 | 0.265 |
| Triglyceride | 1.4 [1.2–2.3] | 2.5 [1.1–3.1] | 1.4 [1.2–1.7] | 0.091 |
| Liver, IU/L | | | | |
| ALP | 98.0 [86.0–132.0] | 99.0 [86.0–115.0] | 97.5 [83.0–132.0] | 0.820 |
| GGT | 37.0 [13.0–71.0] | 23.0 [13.0–114.0] | 40.5 [23.0–63.0] | 0.549 |
| ALT | 28.0 [21.0–47.0] | 23.0 [21.0–39.0] | 34.5 [20.0–49.0] | 0.495 |

Data are presented as mean ± SD **or** n (%) **or** median [25th − 75th percentile].
eGFR = Estimated Glomerular Filtration Rate; UACR = Urine Albumin-to-Creatinine Ratio;
HDL = High-Density Lipoprotein; LDL = Low-Density Lipoprotein; ALP = Alkaline Phosphatase; GGT = Gamma-Glutamyl Transferase; ALT = Alanine Aminotransferase.

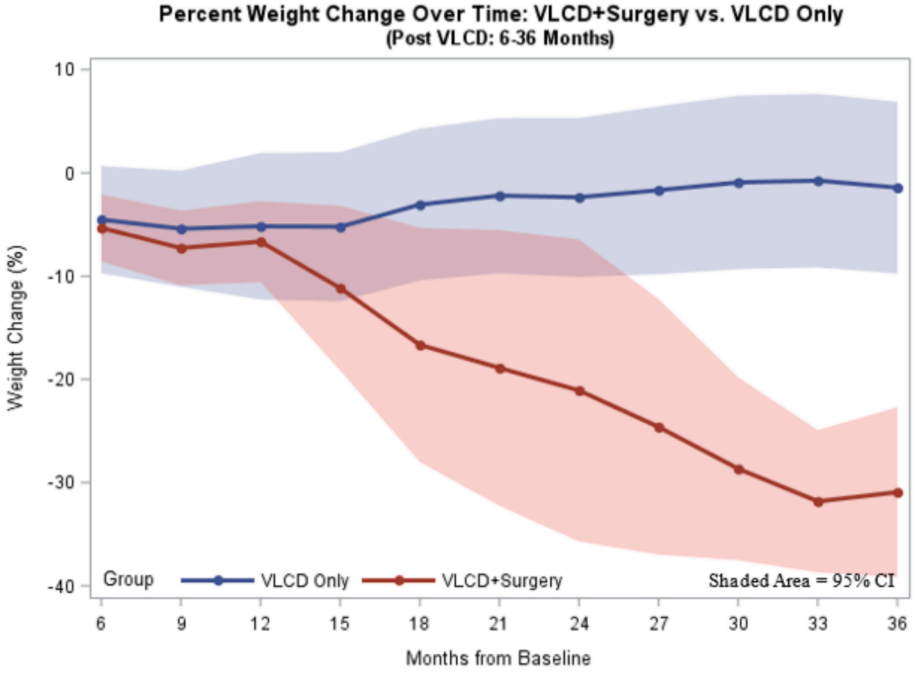


**Fig. 1.** Percent weight change over time − post VLCD.

### 3.3. Sustained effects of bariatric surgery on weight, UACR, and eGFR

Overall, 7 of the 20 participants (35%) progressed to bariatric surgery, with a median (range) interval of 420.0 (329.5–692.5) days between completion of the VLCD and surgery. As shown in Fig. 1, adolescents in the VLCD + Surgery group achieved and sustained significantly greater percentage weight loss compared with those in the VLCD only group (time × group interaction, $p < 0.001$) over the follow-up period beyond 3-months. By 36-months, participants who underwent surgery had lost −30.9% (95% CI: −38.8, –23.1) of baseline body weight, with progressive reduction evident from 12-months onward. In contrast, the VLCD Only group did not achieve significant weight reduction at any timepoint, showing largely flat weight trajectories with occasional mild regain (36-month estimate: −1.7%, 95% CI: −7.4, +4.1; $p = 0.562$).

As shown in Fig. 2, mixed-effects regression of Winsorised log (UACR) demonstrated a significant time × group interaction ($p < 0.001$) during the post-VLCD follow-up period (6–36 months). By 36-months, adolescents in the VLCD + Surgery group had an −83.0% change in UACR from baseline (95%CI: −92.7, −60.4), whereas those in the VLCD Only group showed no significant change (+37.8%, 95%CI: −30.8, 174.2). Estimated trajectories indicated continued reduction in UACR from 24-months onward in the VLCD + Surgery group, whilst mean UACR values in the VLCD Only group remained stable across the follow-up period.

Exploratory covariate-adjusted analyses were undertaken to examine whether differences in UACR trajectories were explained by obesity burden or glycaemic change. In the mixed-effects model including baseline weight and time-varying percent change in HbA1c, HbA1c change was not associated with log(UACR) ($p = 0.9164$), indicating that improvements in albuminuria were not mediated by glycaemic change. Baseline weight was insignificantly associated with log(UACR) (estimate 0.0146, $p = 0.0501$) After adjustment, the bariatric surgery × time interaction was attenuated but remained borderline ($p = 0.0584$).

At enrolment, both groups had mean eGFR values in the hyperfiltration range. Over follow-up, the VLCD + Surgery group showed a downward trend toward the normal eGFR range, whereas the VLCD Only group remained within the high-normal/hyperfiltration range (Fig. 3). However, overall eGFR remained stable with no significant group × time interaction ($p = 0.768$), despite divergent weight and UACR trajectories.

At 36 months, adolescents in the VLCD + Surgery group achieved sustained improvements in weight, glycemia, and metabolic health, with body weight decreasing by ≈ 32% and HbA1c falling from 8.1 to 5.8%. In contrast, the VLCD Only group showed minimal change. Albuminuria and liver enzyme levels declined, triglycerides improved, and eGFR remained stable but above age-expected norms, consistent with baseline hyperfiltration. Overall, combined surgical and lifestyle intervention produced the greatest reno-metabolic benefit (Table 2).

## 4. Discussion

This study examined the renal impact of an intensive 12-week VLCD intervention followed by optional bariatric surgery in adolescents with morbid obesity, most of whom had prediabetes or type 2 diabetes. After up to 36 months of follow-up, adolescents who proceeded to bariatric surgery achieved substantial and sustained weight loss accompanied by significant reductions in albuminuria, compared with those managed with VLCD alone. In contrast, eGFR did not differ significantly between groups, although a non-significant trend towards less hyperfiltration was observed in the VLCD + Surgery group, consistent with attenuation of glomerular hyperfiltration rather than renal impairment. These results provide early longitudinal evidence supporting bariatric surgery as a potential reno-metabolic intervention for youth with severe obesity and type 2 diabetes. The findings are particularly relevant to Māori or Pacific adolescents and likely have global implications for similar high-risk populations, including Indigenous youth in the United States. Expanding access to culturally informed, multidisciplinary obesity-treatment pathways, including surgical options, may help mitigate early DKD risk and reduce health disparities among adolescents with or at risk of type 2 diabetes.

Current Kidney Disease Improving Global Outcomes (KDIGO) and American Diabetes Association (ADA) guidelines emphasise albuminuria as an early indicator of renal risk, even when eGFR is preserved [26,27]. The divergence between albuminuria and eGFR trajectories in our cohort aligns with biological expectations and mirrors paediatric studies reporting improvements in urine albumin excretion without measurable eGFR decline [28].

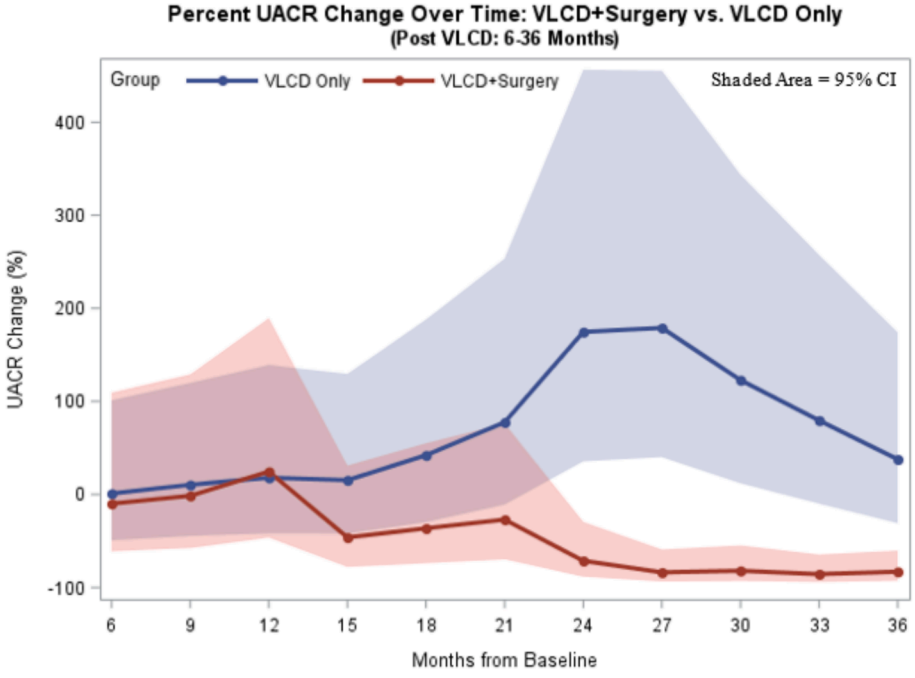


**Fig. 2.** Percent UACR change over time – post VLCD.

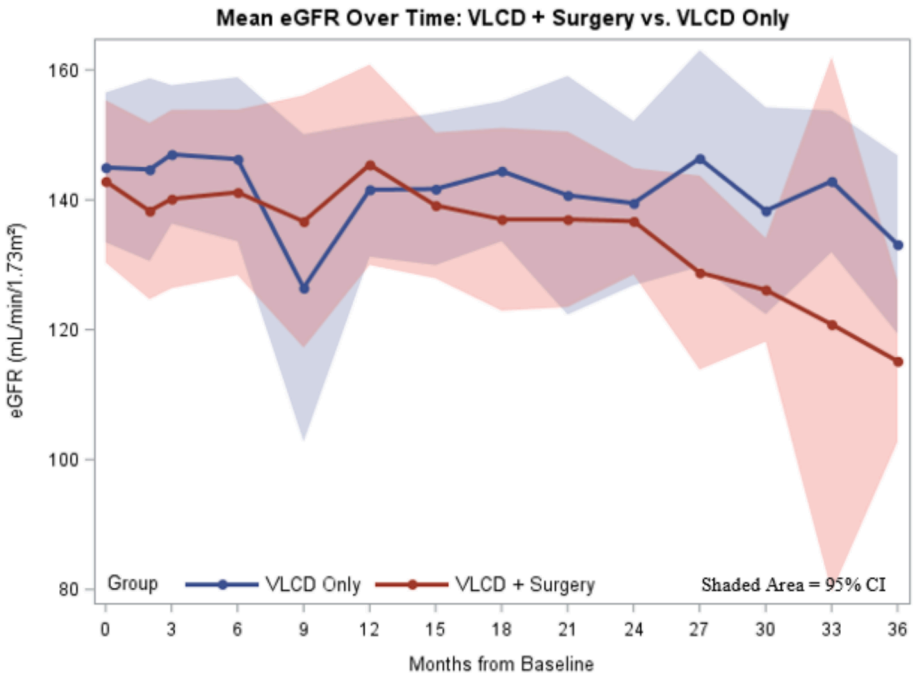


**Fig. 3.** Mean eGFR over time.

**Table 2**
Changes in clinical, metabolic, and renal parameters from baseline to 36 months.

| Characteristic | VLCD + Surgery (n = 7) | | VLCD Only (n = 13) | |
|---|---|---|---|---|
| | Baseline | 36-Months | Baseline | 36-Months |
| Weight, kg | 146.8 ± 28.9 | 99.8 ± 14.1 | 153.0 ± 56.2 | 151.4 ± 63.2 |
| HbA1c, % | 8.1 ± 2.9 | 5.8 ± 0.5 | 7.5 ± 2.2 | 7.1 ± 2.1 |
| HbA1c, mmol/mol | 64.7 ± 32.0 | 39.9 ± 5.0 | 58.4 ± 23.7 | 54.1 ± 22.9 |
| Urate, mmol/L | 0.3 ± 0.1 | 0.4 ± 0.1 | 0.4 ± 0.1 | 0.4 ± 0.1 |
| eGFR, mL/min/1.73 $m^2$ | 142.9 ± 13.5 | 119.0 ± 14.8 | 145.0 ± 19.1 | 132.7 ± 12.9 |
| UACR, mg/mol | 4.6 [0.0–23.2] | 1.8 [1.2–17.3] | 1.9 [0.0–4.9] | 2.1 [0.0–8.7] |
| Lipids, mmol/l | | | | |
| Total Cholesterol | 4.3 ± 0.7 | 3.9 ± 0.9 | 4.3 ± 0.6 | 4.3 ± 0.7 |
| HDL | 1.1 ± 0.3 | 1.3 ± 0.2 | 1.1 ± 0.2 | 1.1 ± 0.2 |
| LDL | 2.1 ± 0.8 | 2.2 ± 0.6 | 2.5 ± 0.5 | 2.7 ± 0.7 |
| Triglyceride | 2.5 [1.1–3.1] | 1.0 [0.7–1.2] | 1.4 [1.2–1.7] | 1.0 [0.7–1.3] |
| Liver, IU/L | | | | |
| ALP | 99.0 [86.0–115.0] | 91 [82.0–102.0] | 97.5 [83.0–132.0] | 86.0 [72.0–96.0] |
| GGT | 23.0 [13.0–114.0] | 15 [10.0–30.0] | 40.5 [23.0–63.0] | 30.0 [20.0–39.0] |
| ALT | 23.0 [21.0–39.0] | 14 [9.0–37.0] | 34.5 [20.0–49.0] | 26.0 [18.0–37.0] |

*Data are presented as mean ± SD* ***or*** *n (%)* ***or*** *median [25th – 75th percentile].*
eGFR = Estimated Glomerular Filtration Rate; UACR = Urine Albumin-to-Creatinine Ratio;
HDL = High-Density Lipoprotein; LDL = Low-Density Lipoprotein; ALP = Alkaline Phosphatase; GGT = Gamma-Glutamyl Transferase; ALT = Alanine Aminotransferase.

In this cohort, although no participant demonstrated impaired renal function at enrolment, 80% exhibited glomerular hyperfiltration (eGFR > 130 mL/min/1.73 $m^2$), a finding consistent with early renal haemodynamic alterations seen in obesity and prediabetes. Hyperfiltration is increasingly recognised as a precursor to DKD, reflecting increased intraglomerular pressure and glomerular hypertrophy that can precede microalbuminuria and subsequent renal decline [29,30]. Although eGFR did not differ significantly between groups over time, the downward trend in the VLCD + Surgery group likely reflects normalisation of glomerular hyperfiltration rather than renal impairment. This interpretation is supported by parallel improvements in UACR and aligns with evidence that bariatric surgery can reverse obesity-related hyperfiltration and improve intrarenal haemodynamics [31,32].

Youth-onset type 2 diabetes is characterised by rapid progression and early development of microvascular complications, including DKD. Nearly all participants in this study had prediabetes or type 2 diabetes by mid-adolescence, reflecting advanced metabolic dysfunction at a young age. These findings parallel evidence from the TODAY, TODAY2, and RISE studies, which demonstrated rapid β-cell failure and limited durability of glycaemic control in adolescents despite intensive pharmacologic therapy [33–35]. Together, these data highlight the difficulty of achieving durable glycaemic control in adolescents through medical management alone.

In contrast, bariatric surgery achieves sustained weight loss and can modify the course of obesity-related complications. In adults, metabolic surgery reduces incident DKD and improves albuminuria and eGFR trajectories [36,37]. Adolescent cohorts such as Teen-LABS and AMOS have similarly reported durable improvements in weight, glycaemia, and cardiometabolic risk factors [38,39]. The present study extends these findings by providing longitudinal evidence that surgery is associated with significant reductions in UACR, a sensitive early indicator of renal improvement, in adolescents with morbid obesity and type 2 diabetes. Adjustment for HbA1c change did not explain the observed improvement in albuminuria, suggesting that renal benefits were not mediated by glycaemia but instead reflect reversal of ORG hyperfiltration and haemodynamic stress. Baseline weight showed a non-significant association with albuminuria, potentially supporting the contribution of underlying obesity burden to renal risk. These findings are consistent with emerging concepts of ORG, in which excess adiposity increases pressure within the glomerulus and promotes sodium retention and inflammation, independent of hyperglycaemia [5,6,8]. Sustained weight reduction may therefore directly modify renal risk pathways before traditional markers of diabetic kidney disease would be expected to change.

Māori and Pacific adolescents in New Zealand bear a disproportionate burden of severe obesity and youth-onset type 2 diabetes, largely

reflecting structural disparities and barriers to preventive and specialty care. The overrepresentation in this cohort underscores both the scale of this disparity and the importance of culturally responsive intervention models. The multidisciplinary framework employed in this study – incorporating family involvement, culturally competent counselling, and psychological support – may be particularly important for improving engagement and outcomes among high-risk youth. These principles are globally relevant, aligning with evidence from Indigenous, Black, and Hispanic communities in the United States, where youth-onset type 2 diabetes and DKD are also increasingly rapidly.

The initial VLCD phase produced meaningful short-term weight loss across all participants, consistent with evidence that VLCDs combined with behavioural support outperform behavioural therapy alone [26]. In adults with type 2 diabetes, VLCD interventions have been associated with partial or complete diabetes remission in up to 40% of cases [40,41], but such effects are rarely durable without continued support or additional intervention. In our cohort, adolescents who did not proceed to surgery experienced weight plateau and partial regain, emphasising that lifestyle-only approaches are unlikely to produce sustained metabolic or renal benefits in severe obesity.

Bariatric (metabolic) surgery remains the most effective intervention for achieving substantial and sustained weight loss and metabolic improvement in severe obesity. Longitudinal studies have demonstrated superior long-term reductions in body weight, HbA1c, and albuminuria compared with intensive medical therapy [36,37]. Surgical procedures such as sleeve gastrectomy and Roux-en-Y gastric bypass confer durable reno-metabolic benefits through mechanisms that extend beyond caloric restriction, including enhanced incretin signalling, improved insulin sensitivity, and reduced glomerular hyperfiltration. There are of course a range of known risks (e.g. surgical complications, electrolytes etc etc), and potentially unknown risk among adolescents.

Recently, GLP-1 receptor agonists and dual incretin agents such as tirzepatide have reshaped the treatment landscape for obesity and type 2 diabetes. Clinical trials including STEP-1 and SURMOUNT-1 in adults have shown 15–20% mean weight loss with improvements in glycaemic and renal parameters [42,43]. However, paediatric data remain limited. The STEP TEENS trial demonstrated significant short-term weight reduction with semaglutide in adolescents with obesity [44], but long-term durability, renal outcomes, and safety in youth with type 2 diabetes are unknown. Furthermore, the RISE study confirmed that even early pharmacologic therapy fails to halt β-cell decline in adolescents, underscoring biological differences between youth- and adult-onset type 2 diabetes [35].

Although pharmacologic options are expanding, bariatric surgery remains the only intervention consistently achieving sustained metabolic and renal improvements in adolescents with severe obesity. Future studies should explore whether GLP-1 receptor agonists or incretin-based agents may serve as adjuncts or bridging therapies before or after surgery, particularly for youth who are ineligible for or awaiting surgical intervention.

Key strengths include the repeated-measures longitudinal design (up to 14 assessments over 36 months) and strong long-term retention, particularly among adolescents who underwent surgery, which is uncommon in adolescent obesity intervention studies [38,45], use of sensitive renal biomarkers, and culturally responsive, multidisciplinary care model. A major strength was the culturally responsive, multidisciplinary framework, incorporating family engagement, dietetic and psychological support, and community-based delivery, designed to address the needs of Māori and Pacific adolescents, who are overrepresented among those with early-onset type 2 diabetes in New Zealand. This approach parallels the challenges faced by culturally and linguistically diverse (CALD) and minority youth in the United States, where early type 2 diabetes also progresses rapidly and is difficult to manage within standard healthcare models [33,35,38,39,46,47].

Limitations include the small sample size and non-randomised design, which may introduce selection bias, as participants who progressed to surgery were required to demonstrate engagement with the programme and psychosocial readiness, and may therefore differ in adherence, motivation, or family support compared with those managed non-surgically. Adherence to the VLCD was supported through regular clinical and dietetic follow-up; however, formal quantitative measures of compliance (e.g., food diaries) were not systematically recorded. As all participants underwent the same structured VLCD programme prior to group divergence, any variability in adherence during this phase is unlikely to fully account for the sustained differences observed during longer-term follow-up. COVID-19 restrictions during the study period posed logistical challenges, including delays in clinic assessments and periodic interruptions to sample collection, resulting in some missing data at later timepoints. UACR at each study visit was measured from a single first-morning urine sample rather than averaging multiple specimens at that timepoint, which may increase susceptibility to short-term biological variability. However, samples were obtained repeatedly over the course of follow-up, allowing assessment of longitudinal change rather than reliance on a single measurement. The analyses therefore focused on model-derived group trajectories with 95% confidence intervals, which account for within-person variation over time. This pragmatic approach reflects routine clinical practice in adolescent weight-management programmes and was applied consistently across study visits and treatment groups, such that any random variability would be expected to bias findings toward the null rather than generate the sustained between-group differences observed. Although eGFR and other renal measures were used, UACR was selected as the primary endpoint due to its sensitivity to early renal injury and its established predictive value for DKD [26,27]. The absence of eGFR decline is not unexpected given the young age and preserved renal reserve of adolescents. Longer-term follow-up is needed to determine whether sustained UACR reductions translate into clinically meaningful differences in renal outcomes [37,38].

In conclusion, these findings contribute new evidence that bariatric surgery, when embedded within structured and culturally appropriate care, may offer early reno-protective benefit in adolescents with or at risk of type 2 diabetes. The consistent relationship between weight loss and reductions in albuminuria strengthens the biological plausibility of this effect. Given the aggressive natural history of youth-onset type 2 diabetes, as shown in the TODAY and RISE trials, early surgical intervention may warrant consideration for selected high-risk adolescents when conventional management fails. Integration of modern pharmacotherapies such as GLP-1 receptor agonists or dual incretin agonists with surgical and behavioural approaches may ultimately define a new paradigm for comprehensive, equity-driven obesity and diabetes care in youth.

## 5. CRediT Authorship contribution Statement:

- Kanchana Perera: Conceptualisation, Formal analysis, Data curation, Methodology, Visualisation, Writing – original draft, Writing – review & editing.
- David Simmons: Conceptualisation, Methodology, Supervision, Writing – original draft, Writing – review & editing.
- John Baker: Conceptualisation, Methodology, Investigation, Data curation, Writing – review & editing.
- Kate Smallman: Investigation, Data curation, Writing – review & editing.
- Karen Pickering: Methodology, Writing – review & editing.
- Patricia Harry: Investigation, Data curation.
- Diana Anderson: Investigation, Data curation.
- Brandon Orr-Walker: Methodology, Writing – review & editing.
- Richard Babor: Funding acquisition, Methodology, Investigation.

David Simmons is the guarantor of this work and, as such, had full access to all data and takes responsibility for the integrity of the data and accuracy of the analysis. All authors reviewed and approved the final

manuscript.

## 6. Prior Presentation

A condensed version of this work was presented as an oral presentation at the New Zealand Society for the Study of Diabetes (NZSSD) conference in Hamilton, New Zealand (14–16 May 2025), and as a poster at the American Diabetes Association (ADA) conference in Chicago, USA (20–23 June 2025).

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## CRediT authorship contribution statement

**Kanchana Perera:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **John Baker:** Writing – review & editing, Methodology, Investigation, Data curation, Conceptualization. **Kate Smallman:** Writing – review & editing, Investigation, Data curation. **Karen Pickering:** Writing – review & editing, Methodology. **Patricia Harry:** Investigation, Data curation. **Diana Anderson:** Investigation, Data curation. **Brandon Orr-Walker:** Writing – review & editing, Methodology. **Richard Babor:** Methodology, Investigation, Funding acquisition. **David Simmons:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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