Neonatal Screening for Congenital Hypothyroidism Based on Thyroxine, Thyrotropin, and Thyroxine-Binding Globulin Measurement: Potentials and Pitfalls

M. J. E. Kempers, C. I. Lanting, A. F. J. van Heijst, A. S. P. van Trotsenburg, B. M. Wiedijk,
J. J. M. de Vijlder, and T. Vulsma

Department of Pediatric Endocrinology (M.J.E.K., A.S.P.v.T., B.M.W., J.J.M.d.V., T.V.), Emma Children's Hospital
Academic Medical Center, University of Amsterdam, 1100 DE Amsterdam, The Netherlands; Department of Prevention and
Healthcare (C.I.L.), Netherlands Organization of Applied Scientific Research, Quality of Life, 2301 CE Leiden, The
Netherlands; and Department of Neonatology (A.F.J.v.H.), Radboud University Nijmegen Medical Centre, 6500 HB
Nijmegen, The Netherlands

Context: The Dutch T_4-TSH-TBG-based neonatal screening program detects patients with congenital hypothyroidism (CH) of thyroidal (CH-T) as well as central (CH-C) origin. The numbers and characteristics of true-positive and false-positive referrals will differ from other, predominantly TSH-based, screening methods.

Objective: The present study describes the characteristics of the referred neonates, both CH patients and false positives, and of the reported CH patients with a false-negative screening result born in the study period.

Design, Setting, Patients, and Main Outcome Measure: For each referred child born between April 1, 2002, and May 31, 2004, screening results and first venous sample results were recorded and classified as transient or permanent CH-T or CH-C or as no CH.

Results: In the study period, 430,764 children were screened. Of the 772 children with abnormal screening results, 224 (29%) had CH;

another 13 CH patients did not have abnormal screening results, giving an overall CH incidence of 1:1800. Incidences of permanent CH, permanent CH-T, permanent CH-C, and transient CH were 1:2200, 1:2500, 1:21,000, and 1:12,000, respectively. The most frequent explanations for the 548 false-positive referrals (71% of the referred cohort) were severe illness and TBG deficiency (occurring in 198 and 200 children, respectively).

Conclusions: The Dutch incidence figures for CH belong to the highest worldwide, suggesting that the T_4-TSH-TBG screening program is an efficient method to detect CH of variable etiology and severity. Still, a small percentage of children with CH escaped detection via this screening approach. Severe illness and TBG deficiency appear to be responsible for the majority of false-positive referrals. (**J Clin Endocrinol Metab 91: 3370–3376, 2006**)

T HYROID HORMONE IS important for normal development of the central nervous system (1). The critical period for the central nervous system to be dependent on thyroid hormone is known to extend from fetal life until at least the first 2 yr after birth (2, 3). Therefore, children with congenital hypothyroidism (CH), if left untreated, are at risk for impaired cognitive and motor development. In many countries, neonatal screening programs have been instituted aiming to prevent cerebral damage by early initiation of T_4 supplementation.

Several countries, such as Japan, Australia, and most European countries, have a TSH-based screening program, whereas many states in North America have a T_4-based screening program with additional measurement of TSH in the samples with the lowest T_4 concentration. Both strategies are capable of detecting CH of thyroidal origin (CH-T), but will miss (the majority of) patients with CH of central origin

(CH-C) (4). Recently, the Dutch T_4-TSH-TBG screening method has proven its outstanding ability to detect patients with CH-T as well as CH-C (5–7), and the extra costs compared with other screening methods are acceptable (4).

In addition to the difference in the proportion of patients with CH-T and CH-C detected by a T_4-TSH-TBG screening method (true positives) compared with other methods, such an approach may also have consequences for the numbers and characteristics of patients with an abnormal screening result but without CH (false positives). In the present study, thyroid hormone determinants and clinical characteristics were analyzed for all children born in a 2-yr period with an abnormal screening result (true and false positives) and of the reported patients with CH not detected by the neonatal screening (false negatives). This design allowed us: 1) to investigate the capability of the T_4-TSH-TBG method to detect CH of various etiology and severity; and 2) to calculate the incidence of various types of CH.

## Patients and Methods

Screening method (Fig. 1)

The Dutch neonatal CH screening method is primarily based on T_4 measurement in filter paper blood spots. Sampling is performed between 4 and 7 d after birth. The concentration of T_4, expressed as SD

FIG. 1. Schematic presentation of the Dutch screening procedure: laboratory tests, interpretation, and decision. *, From January 1, 2005, the cutoff for TSH is lowered from 20 to 18 mU/liter.
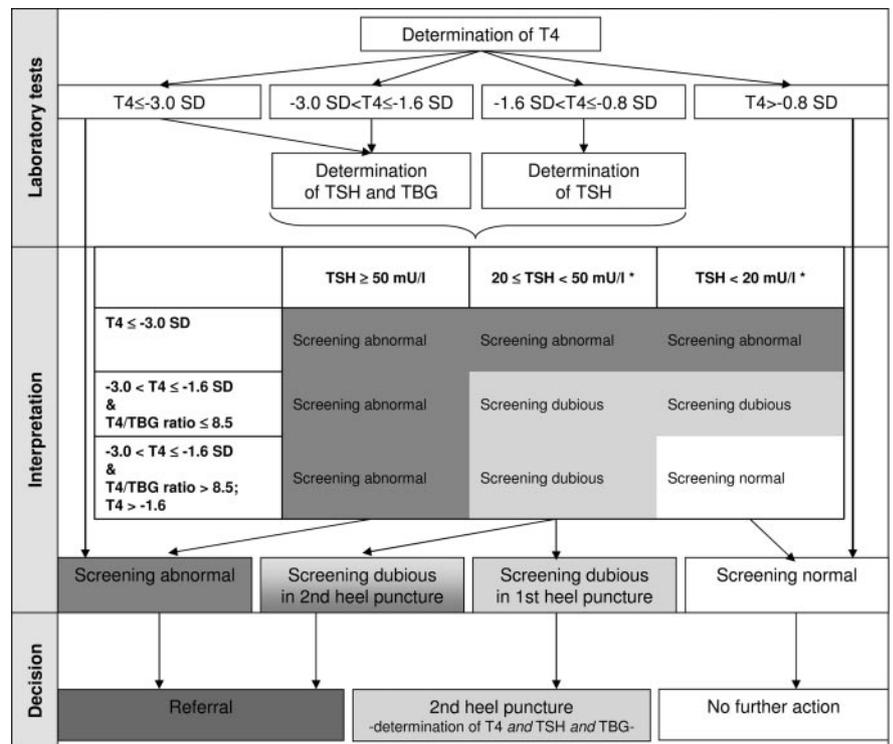
score, is compared with the day mean. If T_4 is -0.8 SD or less, TSH concentration (expressed in microunits per milliliter) is additionally measured. If T_4 is -1.6 SD or less, TBG concentration (expressed in nanomoles per liter) is also measured. A T_4/TBG ratio is calculated as follows: $(T_4 \text{ SD} + 5.1) \times [TBG]^{-1} \times 1000$. If T_4 is -3.0 SD or less or TSH is 50 μU/ml or more, children are immediately referred to a pediatrician. In case of a dubious result ($-3.0 < T_4 \leq -0.8$ SD in combination with a T_4/TBG ratio ≤ 8.5 and/or $20 \leq$ TSH < 50 μU/ml), a second heel puncture is performed and T_4, TSH, and TBG are repeated. Children are referred to a pediatrician after a second heel puncture if the result is dubious again or abnormal (4). For children with a gestational age (GA) of 36.0 wk or less in combination with a birth weight (BW) of 2500 g or less, the referral criterion is based on TSH; if TSH is at least 50 μU/ml, the child is referred, if TSH is at least 20 μU/ml but less than 50 μU/ml, the result is considered dubious and a second heel puncture is performed, after which the child is referred if the result is dubious again or abnormal (4).

In the following text, abnormal screening result refers to one heel puncture sampling with an abnormal screening result or two with a dubious result.

Patients

The study was coordinated and executed by the department of pediatric endocrinology of the Emma Children's Hospital Academic Medical Center (AMC) in collaboration with the Dutch Health Administrations (DHA) and The Netherlands Organization of Applied Scientific Research (TNO). The study protocol was approved by the Institutional Review Board (which judges medical ethical aspects of research proposals) of the AMC and the Privacy Committee of the Dutch CH Screening Board (which judges logistic, scientific, and ethical aspects of research proposals concerning neonatal screening). The studied patients, living all over the country, were not actually referred to the Emma Children's Hospital AMC; only their medical data were recorded.

When a child is born in The Netherlands, parents get a heel puncture package with written information upon registering the birth of their child. When the health worker visits the parents' home, the heel puncture is performed only after parents give their implicit consent.

The regional CH screening laboratory notifies the DHA on abnormal and dubious CH screening results. Whenever referral to a pediatrician is indicated, the DHA immediately contacts the general practitioner. For those children born from April 1, 2002, until May 31, 2004 (referred to as the study period), with an indication for referral, the DHA has sent faxes with data containing heel puncture results, GA, BW, and the name of the general practitioner to the AMC. This enabled the researchers of the AMC to contact the pediatrician and ask for the laboratory and clinical data of the referred child.

TNO documents the screening results and diagnostic findings of Dutch children with abnormal screening results and data of CH patients missed by neonatal screening, when reported by pediatricians. All local hospitals can determine free T_4 (FT_4) and TSH, but for less common thyroid function tests (such as TBG, thyroglobulin, or T_3), material has to be sent to a few specialized laboratories (*e.g.* the AMC). Tests for urinary iodine and low-molecular-weight iodinated material are exclusively performed in the AMC. The AMC keeps records of patients whose blood or urine samples were sent to confirm or specify the diagnosis of CH or whose pediatrician consulted the Department of Pediatric Endocrinology for advice. Usually this concerns referred patients with abnormal CH screening results, but occasionally the records belong to CH patients with normal screening results (false negatives). To get the most complete cohort of CH patients born in the study period, datasets of TNO and AMC were combined.

Classification based on screening results and diagnostic work-up

For all subjects born during the study period, CH screening results, first venous plasma FT_4 and TSH (and optionally TBG), GA, BW, and any remarkable clinical characteristics (*e.g.* family history and maternal thyroid function) were recorded. Based on the provided information, diagnosis was classified as no CH, transient CH, or permanent CH. The category of no CH was subdivided according to the alleged reason of the abnormal screening result: severe illness, TBG deficiency (total when heel puncture TBG was <0.3 mg/dl, *i.e.* <50 nmol/liter; partial when 0.3 mg/dl $\leq$ heel puncture TBG < 1.8 mg/dl, *i.e.* 50 $\leq$ TBG < 300 nmol/liter), errors in the screening procedure, exchange blood transfusion, delayed blood sampling, pre-/dysmaturity, and no obvious explanation. The diagnosis of transient CH was further classified into transient CH-T or transient CH-C. When known, the cause of transient CH was documented. The diagnosis of permanent CH was further classified into CH-T, CH-T21 (*i.e.* CH-T related to trisomy 21) (8), CH-C, or CH not yet specified.

Reference ranges for children born at term at the age of 2–6 wk for T_4, FT_4, TSH, and TBG are 6.5–16.3 μg/dl (84–210 nmol/liter), 0.9–2.2 ng/dl (12–28 pmol/liter), 1.7–9.1 μU/ml, and 1.0–4.5 mg/dl (160–750 nmol/liter), respectively (9). For 2-wk-old preterm children, the reference ranges of T_4, FT_4, and TSH (mean ± SD) of Williams *et al.* (10) were adopted: for GA 23–27 wk, T_4 is 4.7 ± 2.6 μg/dl (61 nmol/liter), FT_4 is 1.4 ± 0.5 ng/dl (18.6 pmol/liter), and TSH is 3.9 ± 2.7 mU/liter; for GA 28–30 wk, T_4 is 6.6 ± 2.3 μg/dl (85 nmol/liter), FT_4 is 1.6 ± 0.4 ng/dl (21.2 pmol/liter), and TSH is 4.9 ± 11.2 mU/liter; and for GA 31–34 wk, T_4 is 9.1 ± 3.6 μg/dl (117 nmol/liter), FT_4 is 2.0 ± 0.4 ng/dl (25.2 pmol/liter), and TSH is 3.8 ± 9.3 mU/liter.

Results

Between April 1, 2002, and May 31, 2004, 432,082 children were born in The Netherlands of whom 430,764 (99.7%) participated in the neonatal screening program. In total, 772 children (one for every 558 screened children) with an abnormal CH screening result were referred, 534 after one heel puncture, 238 after the second one. In 190 patients (25%) permanent CH and in 34 (4%) transient CH was diagnosed (Table 1). Of those children referred because of T_4 of −3.0 SD or less (n = 474), 72 (15%) had permanent CH, 12 (3%) had transient CH, and 390 (82%) had no CH (Table 1). All 112 patients with TSH of at least 50 μU/ml had CH-T, of whom the majority (n = 110) were diagnosed permanent (Table 2).

Within the permanent CH group, 72 patients (38%) had T_4 of −3.0 SD or less (Table 1) and 110 (58%) had TSH of at least 50 mU/liter (Table 2); 34 (18%) had TSH less than 20 mU/liter (Table 2), of whom 15 had CH-C, 13 CH-T, and six CH not yet specified.

No CH

Of the 548 children classified as no CH, 436 (80%) had GA more than 36.0 wk and BW more than 2500 g, 49 (9%) had GA more than more than 36.0 wk and BW of 2500 g or less, 61 (11%) had GA of 36.0 wk or less and BW more than 2500 g, and two had GA of 36.0 wk or less and BW of 2500 g or less (Table 3).

In the group with no CH, 198 children (36%) were already hospitalized because of severe illness. The primary indications for hospitalization were asphyxia (n = 28), pulmonary problems (n = 61; in 31, extracorporeal membrane oxygenation was necessary), congenital heart defect (n = 23), neurological problems (n = 5), gastrointestinal problems (n = 11), sepsis (n = 12), surgery not otherwise specified (n = 6),

TABLE 2. Classification of CH according to the (first) heel puncture TSH

Heel puncture TSH (μU/ml)	Classification of CH			n
	No CH	Transient CH	Permanent CH	
TSH ≥ 50	0	2	110	112
20 ≤ TSH < 50	1	19	46	66
TSH < 20	547	13	34	594
Total	**548**	**34**	**190**	**772**

dysmorphic features (n = 3), or syndromes (n = 2). In 47 cases, the indication was not specified. Heel puncture T_4, TSH, and TBG in the group with no CH ranged from 0.8–8.2 μg/dl (10–106 nmol/liter), 0.16–18.4 μU/ml, and 0.3–3.7 mg/dl (42–613 nmol/liter), respectively; venipuncture FT_4 and TSH, measured within 7 d after the heel puncture, ranged from 0.4–3.0 ng/dl (5.1–38.6 pmol/liter) and 0.16–18.4 μU/ml, respectively.

TBG deficiency was diagnosed in 200 children (36% of those with no CH), of whom 77 (39%) had total TBG deficiency. Plasma FT_4 measured in the first venous blood sample ranged from 0.5–3.7 ng/dl (6.3–47.8 pmol/liter). Of the nine children with FT_4 less than 0.9 ng/dl (<12 pmol/liter), eight had total TBG deficiency at verification and one had a very low TBG (0.3 mg/dl; 58 nmol/liter) in the heel puncture (no confirmatory TBG was available). Of the 12 children with a plasma FT_4 more than 2.3 ng/dl (>30 pmol/liter), 11 had a total TBG deficiency (TBG < 0.3 mg/dl).

In seven children, an error was made in the screening procedure: in two, both 36.0 wk GA or less and 2500 g BW or less, their GA and BW were not reported correctly on the filter paper; in two, initial T_4 determination, upon which the child was referred, turned out to be normal after repeated measurement on the same heel puncture sample (executed because of the mismatch between the results of heel puncture and venous blood sampling); in one, a second heel puncture, with an abnormal result, was performed despite a normal first result; in two, both with T_4 of −3.0 SD or less and normal TSH, the filter paper blood spots arrived at the laboratory with a delay of more than 2 wk.

In 57 children, the abnormal screening results could be ascribed to an exchange blood transfusion (n = 2), a delay of more than 2 wk in heel puncture sampling (n = 9), low BW (≤2500 g) in combination with normal GA (>36.0 wk) with-

TABLE 1. Classification of CH according to the (first) heel puncture T_4

Heel puncture measurements		Interpretation			No. of referrals
T_4 (SD)	TSH (μU/ml)	No CH	Transient CH	Permanent CH	
T_4 ≤ −3.0	TSH ≥ 50	0	0	53	53
	20 ≤ TSH < 50	1	7	3	11
	TSH < 20	389	5	16	410
Subtotal		390	12	72	474
−3.0 < T_4 ≤ −0.8	TSH ≥ 50	0	2	57	59
	20 ≤ TSH < 50	0	12	43	55
	TSH < 20[a]	158	8	18	184
Subtotal		158	22	118	298
Total (of 430,764 screened neonates)		**548**	**34**	**190**	**772**
Percentage		71	4	25	100

[a] In combination with a T_4/TBG ratio of ≤8.5 (see also Fig. 1).

TABLE 3. Most likely explanation for the abnormal screening results of the 548 referred neonates of 430,764 screened neonates diagnosed as no CH

Explanation for abnormal screening result	GA and BW			Total (n)
	GA > 36.0 wk, BW > 2500 g	GA > 36.0 wk, BW ≤ 2500 g	GA ≤ 36.0 wk, BW > 2500 g	
Severe illness	144	27	27	198
TBG deficiency	191	6	3	200
Error in screening procedure	5	0	0	7[c]
Exchange blood transfusion[a]	1	0	1	2
Delayed sampling[b]	9	0	0	9
Prematurity or dysmaturity	0	16	30	46
No obvious explanation	86	0	0	86
Total, n (%)	**436 (80)**	**49 (9)**	**61 (11)**	**548[c] (100)**

[a] Compared with neonatal blood, adult donor used during exchange blood transfusion contains a lower T_4 concentration.

[b] Heel puncture was more than 2 wk delayed. Because, after an initial peak shortly after birth, plasma FT_4 concentration gradually decreases (14), this was considered the reason for the abnormal CH screening result.

[c] Two children were born 36.0 wk GA or earlier and with 2500 g or less BW, but their GA and BW were not reported correctly on the filter paper.

out severe illness (n = 16) and low GA (≤36.0 wk) in combination with normal BW (>2500 g) without severe illness (n = 30).

In the remaining 86 children, there was no obvious reason for the abnormal screening results. Their heel puncture T_4 concentration ranged from 4.8–10.3 μg/dl (62–133 nmol/liter) with TSH 2–10 μU/ml and TBG 1.8–4.1 mg/dl (305–678 nmol/liter).

Transient CH

In 34 patients, the abnormal CH screening result led to the diagnosis of transient CH.

Twenty-four were diagnosed with transient CH-T. Their heel puncture T_4 varied from 0.8–13.1 μg/dl (10–169 nmol/liter) and TSH varied from 18–67 μU/ml. Nine patients were born 36.0 wk GA or earlier, of whom six had BW of 2500 g or less. Six patients had been exposed to excessive amounts of iodine during cesarean section (n = 1), neonatal surgery (n = 4), and treatment with amiodarone because of cardiac arrhythmia (n = 1); two patients were born to a mother with autoimmune thyroid disease.

Ten were diagnosed with transient CH-C. Their heel puncture T_4 varied from 2.7–9.0 μg/dl (35–120 nmol/liter), TSH 2–12 μU/ml, and TBG 1.7–4.0 mg/dl (288–657 nmol/liter). All mothers appeared to have Graves' disease; six were diagnosed before pregnancy but inadequately treated throughout pregnancy; in four, Graves' disease remained unrecognized until their child was diagnosed with CH-C.

Permanent CH

In 190 patients, the abnormal CH screening result led to the diagnosis of permanent CH; 16 patients were born 36.0 wk GA or earlier, of whom 11 had BW of 2500 g or less; 11 had BW of 2500 g or less and GA more than 36.0 wk.

In this group, 151 patients (79%) had CH-T, 15 patients (8%) had CH-T21, and 15 patients (8%) had CH-C. In the CH-T group, 78 (52%) had thyroid dysgenesis and 21 (14%) had thyroid dyshormonogenesis, and in 52 (34%), the diagnosis is not yet further specified (Table 4). In the CH-C group, one patient had septo-optic dysplasia and one had trisomy 13.

In nine of the 190 patients (5%), insufficient data were avail-

able to classify the origin of the CH as thyroidal or central: one patient had a congenital nephrotic syndrome (in fact a type of CH caused by the loss of thyroid hormone in the urine) and one had Xp22 deletion with partial trisomy 19p.

CH with normal CH screening result (Table 5)

Three patients (nos. 1 and 2 with permanent CH-T and no. 3 with transient CH-C) had already started T_4 supplementation before the heel puncture was performed. Ten patients had false-negative screening results.

In one patient with permanent CH-T (no. 4), hypothyroidism was too mild for detection by screening. The coexistence of Johansson-Blizzard syndrome led to the diagnosis of CH. The other patient with permanent CH-T (no. 5) was supported by a heart-lung machine at the time of heel puncture sampling because of a congenital heart defect. Routine thyroid function determination after weaning led to the diagnosis of CH.

Of the six patients with permanent CH-C, two were diagnosed in the first year after birth because of failure to thrive (nos. 6 and 7); three, of whom two were born at 36.0 wk GA or earlier with a BW of 2500 g or less, were diagnosed with CH-C because of the coexistence of Cornelia de Lange syn-

TABLE 4. Etiology of permanent CH

Etiology	n
CH-T due to thyroid dysgenesis	78 (78, 0)
CH-T due to thyroid dyshormonogenesis	23 (21, 2)
CH-T not yet specified	54 (52, 2)
CH-T$_{21}$	15 (15, 0)
CH-C	21 (15, 6)[a]
CH not yet specified	9 (9, 0)
Total	200 (190, 10)[a]

For each etiology, the number of patients is presented. The *numbers in parentheses* represent the number of patients diagnosed by screening (first number) and the number of patients with a normal CH screening result (second number, further specified in Table 5). Thyroid dysgenesis means agenesis or hypoplastic or dystopic rudiment. CH-T not yet specified means that imaging studies were not conclusive about the etiology; CH not yet specified means CH had not yet been classified as CH-T or CH-C.

[a] Children with transient CH-C due to maternal Graves' disease are not included (see Table 5).

TABLE 5. Reason that CH screening was not abnormal and clue to the diagnosis of CH in the patients with normal CH screening result

ID	Type of CH	Reason that CH screening result was not abnormal	Clue to the diagnosis of CH	Heel puncture result			
				T_4 [μg/dl (nmol/liter)]	T_4 (SD)	TSH (μU/ml)	T_4/TBG ratio
1	CH-T	Diagnosis and start of T_4 supplementation before screening	Sib with CH-T	15.8 (203)	−0.2		
2	CH-T	Diagnosis and start of T_4 supplementation before screening	Sib with CH-T	8.2 (105)	−1.4	24	
3	CH-C[a]	Diagnosis and start of T_4 supplementation before screening	Maternal Graves' disease	15.3 (197)	1.0		
4	CH-T	Too mild for detection	Sib with CH-T and Johansson-Blizzard syndrome	9.9 (128)	−0.6		
5	CH-T	Support by heart-lung machine	Routine thyroid function determination	3.1 (40)	−2.6	5	12.4
6	CH-C	Too mild for detection	Failure to thrive	9.6 (123)	−1.1	3	
7	CH-C[b]	Too mild for detection	Failure to thrive	6.4 (82)	−2.0	7	8.3
				5.0 (64)	−2.4	8	9.2
8	CH-C	GA ≤ 36 wk and BW ≤ 2500 g	Cornelia de Lange syndrome	9.6 (123)	−0.7		
9	CH-C	GA ≤ 36 wk and BW ≤ 2500 g	Microgenitalism	4.3 (55)	−2.7	3	9.0
10	CH-C	Too mild for detection	Prader-Willi syndrome	10.9 (140)	−0.7		
11	CH-C	Too mild for detection	Twin brother diagnosed with CH-C	9.6 (124)	−1.2	5	
12	CH-C[a]	GA ≤ 36 wk and BW ≤ 2500 g	Maternal Graves' disease	3.7 (47)	−3.0	3	5.7
13	CH-C[a]	GA ≤ 36 wk and BW ≤ 2500 g	Maternal Graves' disease	1.2 (16)	−4.2	<3	4.2

In the first three patients, CH screening results were in fact true normal because T_4 supplementation had already started before screening. Their FT_4 concentrations before treatment were 1.1, 0.7, and 0.7 ng/dl and their TSH concentrations were 19.8, 295, and 3.8 mU/liter, respectively. In the other 10 patients, the CH screening result was really false negative. ID, Numbers that refer to those mentioned in the text.
[a] Refers to transient CH; all other cases are permanent.
[b] In this patient, the *top numbers* refer to the first heel puncture, and the *bottom numbers* to the second heel puncture.

drome (no. 8), microgenitalism (no. 9), or Prader-Willi syndrome (no. 10); one (no. 11) was diagnosed after the diagnosis CH-C in his twin brother was made (with an abnormal CH screening result).

In two patients with transient CH-C (nos. 12 and 13) born to mothers with inadequately treated Graves' disease, screening results were not judged abnormal because of the restricted referral criteria in children with GA of 36.0 wk or less and BW of 2500 g or less.

Discussion

In 224 (29%) of the 772 children born between April 1, 2002, and May 31, 2004, and referred because of abnormal screening results, the diagnosis CH, either permanent or transient, could be confirmed. Another 13 CH patients, born in the same period, were not detected by screening. Of them, three children started with T_4 supplementation before heel puncture was performed, and 10 had false-negative screening results. Sensitivity and specificity of the Dutch screening approach were 95.8 and 99.9%, respectively.

Among the 430,764 screened children, the incidence of CH was 1:1,800, of whom 85% had permanent CH (incidence 1:2,200). The incidences of permanent CH-T (1:2,500) and permanent CH-C (1:21,000) in the present 2002–2004 cohort are quite similar to those calculated for the cohort of 346,335 children screened in 1981–1982 (1:2,900 and 1:22,000, respectively) (11). These incidence figures belong to the highest worldwide. Because there is no reason to assume that the Dutch population has a higher risk of developing CH compared with other well-developed, iodine-repleted countries,

the high number of patients found is most probably the result of an efficient screening method detecting CH of variable etiology, including mild cases. The incidence of transient CH is 5- to 6-fold reduced from 1:2,200 in 1981–1982 (11) to 1:12,000 at present. This substantial reduction is probably because of the reduced perinatal use of iodine-containing disinfectants and possibly because of reduced use of iodine-containing x-ray contrast agents.

We classified children with CH-C resulting from inadequately treated maternal Graves' disease as having transient CH-C because it has been reported that pituitary function recovers after some time (12, 13). From our present data, an incidence of 1:33,000 for transient CH-C related to maternal Graves' disease could be calculated (n = 13), which is substantially higher than in 1981–1982, when only one of 346,335 screened children had been diagnosed with this type of CH (11). We have to be aware that even in the present cohort some cases might have escaped diagnosis. In four mother-child pairs, the abnormal neonatal screening result was the first clue to both the infant's thyrotropic dysfunction and the mother's thyroid disease. Therefore, whenever CH-C is suspected, we recommend screening the mother for thyroid disease in addition to screening of the child for additional pituitary hormone deficiencies (5).

In two previous publications, it was concluded that the Dutch T_4-TSH-TBG screening approach provided an excellent strategy to detect CH of thyroidal as well as central origin (4, 6). In the present cohort, early detection would have failed in 47 CH patients, including 15 patients with permanent CH-C, if an elevated TSH concentration had been used

as the only referral criterion. Especially in permanent CH-C, early detection is of vital importance because of the possible coexistence of other pituitary hormone deficiencies for which adequate and timely supplementation will reduce morbidity and prevent mortality.

The relatively high number of referred children in whom the diagnosis of hypothyroidism could not be confirmed at the time of referral is considered a drawback of the T_4-TSH-TBG approach. In over one third of these false-positive cases, partial or total TBG deficiency was diagnosed. We chose a cutoff of 1.8 mg/dl (300 nmol/liter) for the diagnosis of partial TBG deficiency, even though this is higher than the lower limit of the reference range as reported in the literature of 1.3 mg/dl (14) and 1.0 mg/dl (9) in children aged 2–6 wk. However, because of the high-affinity binding between T_4 and TBG, we hold the relatively low TBG responsible for the low heel puncture T_4 in these children. Determination of TSH and TBG in all children with T_4 of −3.0 sp or less before the indication for referral was made could have prevented referral of all 77 cases with total TBG deficiency. However, this would have caused impermissible delay in referral of those children with severe CH.

In general, TBG deficiency is considered a harmless condition, not influencing thyroid function. Nevertheless, in children with total TBG deficiency, we often encountered FT_4 concentrations below as well as above the reference range, dependent on the FT_4 assay used. Indeed, methodological limitations might make FT_4 assays unreliable in case of total absence of TBG (15, 16). Therefore, the diagnosis of TBG deficiency should be based on determination of plasma TBG rather than FT_4.

The other major subgroup of referred children in whom none of the classical types of CH could be diagnosed (about one fourth of all referrals) consisted of severely ill neonates hospitalized on an intensive care unit at the time of heel puncture sampling. Most likely, their severe illness was responsible for the decreased heel puncture T_4, whereas medication or the use of iodine might have transiently disturbed their thyroid hormone state (17, 18). The decreased heel puncture T_4 in these severely ill children somewhat resembles that of children born prematurely (19). Because early postnatal T_4 levels are strongly related to GA and BW (20, 21), Dutch children born 36.0 wk or earlier and at 2500 g or less BW are referred only if screening TSH is elevated. Using this TSH-only referral criterion also for severely sick children born at term would have prevented the majority of referrals in this group. This evokes some important considerations. First, these patients can only be considered as truly false positives when the altered thyroid hormone state does not carry a risk of (preventable) brain damage. Although it is still a matter of debate whether adult patients with so-called nonthyroidal illness benefit from T_4 supplementation (22, 23), it is as yet unknown whether neonates with severe illness might benefit especially from T_4 supplementation in terms of reduction of long-term morbidity and preservation of brain development. Furthermore, like in preterm born children, such adapted referral criteria will hamper the (timely) diagnosis of CH-C.

Indeed, during the study period, we encountered four preterm children with proven CH-C not detected by screen-

ing because of the TSH-only approach for this group. On the other hand, also in four term children with CH-C, heel puncture T_4 concentrations did not indicate referral. The coexistence of a syndrome, microgenitalism, failure to thrive, maternal Graves' disease, or a family member with CH-C led to the diagnosis of CH-C.

The relatively short observational period is considered a limitation in the detection of false negatives. In the forthcoming years, more false-negative cases might be identified. The measurement of T_4, TSH, and TBG in all heel puncture samples will provide the highest chance of detecting patients with various types of CH (including central CH) as well as cases with mild CH (including those with normal T_4 concentrations but elevated TSH). However, this will be a very costly approach and presumably hardly any extra patient will be discovered with a preventable risk of brain damage. Furthermore, with such an approach, patients with mild CH-C may still escape detection, whereas also some patients with delayed TSH elevation still escape early detection (as was presumably the case in patient no. 5 in Table 5).

The present study showed that in 15 patients with trisomy 21, CH was detected by screening, *i.e.* about 3% of the patients with trisomy 21 born in the study period. This is quite similar to the 3.5% reported by van Trotsenburg *et al.* (24) in a cohort of Dutch patients with trisomy 21 born in 1996–1997. Recently, it has been shown that as a group, these patients have a persistent mild type of CH, presumably of thyroidal origin (CH-T21) and that T_4 supplementation started early subtly improves early motor development and growth (8, 25). This indicates that also in patients with mild CH not related to trisomy 21, it should be established whether T_4 supplementation is beneficial for brain development.

In summary, the T_4-TSH-TBG screening method as used in The Netherlands has the potential to detect CH of thyroidal as well as of central origin, either permanent or transient, severe or mild. The Dutch incidence figures belong to the highest worldwide, both for CH-T and CH-C. Among the referred children in whom the diagnosis of CH could not be confirmed, TBG deficiency and severe illness could be held responsible for the great majority of low heel puncture T_4 concentrations.

An important pitfall of any screening method is the occurrence of false-negative results. For the Dutch CH screening in particular, this pitfall concerns children with very mild types of CH having T_4 concentrations within the normal range and prematurely born babies with CH-C.

Neonatal screening has proven its benefits in terms of improving development in patients with the classical types of (severe) CH. Future studies should focus on severely ill neonates and the very mild cases of CH-T and CH-C to investigate whether these patients might also benefit from (temporary) T_4 supplementation in terms of reduction of morbidity or improvement of developmental outcome.

Address all correspondence and requests for reprints to: Marlies J. E. Kempers, M.D., Academic Medical Center, University of Amsterdam, G8-205, Emma Children's Hospital AMC, Department of Pediatric Endocrinology, P.O. Box 22700, 1100 DE Amsterdam, The Netherlands. E-mail: m.j.kempers@amc.uva.nl.

References

1. **Bernal J** 2002 Action of thyroid hormone in brain. J Endocrinol Invest 25:268–288
2. **Porterfield SP, Hendrich CE** 1993 The role of thyroid hormones in prenatal and neonatal neurological development–current perspectives. Endocr Rev 14:94–106
3. **Zoeller RT, Rovet J** 2004 Timing of thyroid hormone action in the developing brain: clinical observations and experimental findings. J Neuroendocrinol 16:809–818
4. **Lanting CI, van Tijn DA, Loeber JG, Vulsma T, de Vijlder JJ, Verkerk PH** 2005 Clinical effectiveness and cost-effectiveness of the use of the thyroxine/thyroxine-binding globulin ratio to detect congenital hypothyroidism of thyroidal and central origin in a neonatal screening program. Pediatrics 116:168–173
5. **Kempers MJ, van Tijn DA, van Trotsenburg AS, de Vijlder JJ, Wiedijk BM, Vulsma T** 2003 Central congenital hypothyroidism due to gestational hyperthyroidism: detection where prevention failed. J Clin Endocrinol Metab 88:5851–5857
6. **van Tijn DA, de Vijlder JJ, Verbeeten Jr B, Verkerk PH, Vulsma T** 2005 Neonatal detection of congenital hypothyroidism of central origin. J Clin Endocrinol Metab 90:3350–3359
7. **Fisher D** 2005 Next generation newborn screening for congenital hypothyroidism? J Clin Endocrinol Metab 90:3797–3799
8. **van Trotsenburg ASP, Kempers MJE, Endert E, Tijssen JGP, de Vijlder JJM, Vulsma T,** Trisomy 21 causes persistent congenital hypothyroidism presumably of thyroidal origin. Thyroid, in press
9. **Fisher DA** 1991 Management of congenital hypothyroidism. J Clin Endocrinol Metab 72:523–529
10. **Williams FL, Simpson J, Delahunty C, Ogston SA, Bongers-Schokking JJ, Murphy N, van Toor H, Wu SY, Visser TJ, Hume R; Collaboration from the Scottish Preterm Thyroid Group** 2004 Developmental trends in cord and postpartum serum thyroid hormones in preterm infants. J Clin Endocrinol Metab 89:5314–5320
11. **Vulsma T** 1991 Etiology and pathogenesis of congenital hypothyroidism: evaluation and examination of patients detected by neonatal screening in The Netherlands. PhD thesis, University of Amsterdam, Amsterdam
12. **Matsuura N, Harada S, Ohyama Y, Shibayama K, Fukushi M, Ishikawa N, Yuri K, Nakanishi M, Yokota Y, Kazahari K, Oguchi H** 1997 The mechanisms of transient hypothyroxinemia in infants born to mothers with Graves' disease. Pediatr Res 42:214–218
13. **Hashimoto H, Maruyama H, Koshida R, Okuda N, Sato T** 1995 Central hypothyroidism resulting from pituitary suppression and peripheral thyrotoxicosis in a premature infant born to a mother with Graves disease. J Pediatr 127:809–811
14. **Elmlinger MW, Kuhnel W, Lambrecht HG, Ranke MB** 2001 Reference intervals from birth to adulthood for serum thyroxine (T4), triiodothyronine (T3), free T3, free T4, thyroxine binding globulin (TBG) and thyrotropin (TSH). Clin Chem Lab Med 39:973–979
15. **Stockigt JR** 2001 Free thyroid hormone measurement: a critical appraisal. Endocrinol Metab Clin North Am 30:265–289
16. **Bruin T, Huigen HJ, Endert E** 1999 [Remarks on the determination of free T4]. Ned Tijdschr Klin Chem 24:326–328 (Dutch)
17. **Stewart DL, Ssemakula N, MacMillan DR, Goldsmith LJ, Cook LN** 2001 Thyroid function in neonates with severe respiratory failure on extracorporeal membrane oxygenation. Perfusion 16:469–475
18. **Lim DJ, Herring MK, Leef KH, Getchell J, Bartoshesky LE, Paul DA** 2005 Hypothyroxinemia in mechanically ventilated term infants is associated with increased use of rescue therapies. Pediatrics 115:406–410
19. **van Wassenaer AG, Kok JH** 2004 Hypothyroxinaemia and thyroid function after preterm birth. Semin Neonatol 9:3–11
20. **Hume R, Simpson J, Delahunty C, van Toor H, Wu SY, Williams FL, Visser TJ; Scottish Preterm Thyroid Group** 2004 Human fetal and cord serum thyroid hormones: developmental trends and interrelationships. J Clin Endocrinol Metab 89:4097–4103
21. **Kok JH, Hart G, Endert E, Koppe JG, de Vijlder JJ** 1983 Normal ranges of T4 screening values in low birthweight infants. Arch Dis Child 58:190–194
22. **Stathatos N, Levetan C, Burman KD, Wartofsky L** 2001 The controversy of the treatment of critically ill patients with thyroid hormone. Best Pract Res Clin Endocrinol Metab 15:465–477
23. **De Groot LJ** 2006 Non-thyroidal illness syndrome is a manifestation of hypothalamic-pituitary dysfunction, and in view of current evidence, should be treated with appropriate replacement therapies. Crit Care Clin 22:57–86
24. **van Trotsenburg AS, Vulsma T, van Santen HM, Cheung W, de Vijlder JJ** 2003 Lower neonatal screening thyroxine concentrations in Down syndrome newborns. J Clin Endocrinol Metab 88:1512–1515
25. **van Trotsenburg AS, Vulsma T, van Rozenburg-Marres SL, van Baar AL, Ridder JC, Heymans HS, Tijssen JG, de Vijlder JJ** 2005 The effect of thyroxine treatment started in the neonatal period on development and growth of two-year-old Down syndrome children: a randomized clinical trial. J Clin Endocrinol Metab 90:3304–3311