Analysis on the interference assembly of camshaft with knurled tube and cam

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Abstract
Interference joint is one of the most advanced assembly methods for camshaft. The joining force in the assembly process and the connection strength after assembly are the key aspects of the camshaft assembly system. In this paper, the mechanism of joining force and connection strength are analyzed from two aspects of elasticity and plasticity using thick-wall cylinder model. Joining and torsion experiments are done to determine the joining force and connection strength. Joining forces fluctuating increase in the joining process, which is composed by friction force \( F_s \) and shearing force \( F_f \). \( F_s \) is 0.87 KN, and \( F_f \) is 6.23 KN when the assembly interference is 0.15mm. Joining force linear increases with the interference, and torque exponential increases with it. The empirical formulas between the torque capacity, joining force, and interference of the camshaft are provided by the experiment results. The assembly interference limit of 0.3mm is estimated for the case of this paper. Metallographic observation reveals the changes of metal flow line of the knurled tube. The top of knurled tooth turns over and an inverted triangle formed after joining process.

Keywords Interference assembly · Camshaft · Knurling · Joining force · Connection strength

1 Introduction
As the key part of the engine valve, camshaft has an important influence on the volume of intake air, dynamic performance, and gas emission of the engine [1]. Camshaft is divided into two types: integral camshaft and assembled camshaft. The integral camshaft is manufactured by casting, powder sintering, or forging. For the assembled camshaft, the cam and shaft are manufactured separately and then assembled. Assembled camshaft has significant advantages comparing with the integral camshaft, such as weight reduction, material optimization, production cost, and energy saving. Recent developments in lightweight vehicles have heightened the needs for assembled camshaft [2, 3].

Several assembly technology for camshaft have been proposed, which includes shrink fit assembling, welding, bonding, mechanical expanding joint, hydraulic expanding joint, etc [4, 5]. Additional heat is required in both shrink fit assembling and welding process. It is difficult to control the assembly accuracy, and results in uncertainty of the joint reliability [6]. Bonding, mechanical expanding, and hydraulic expanding joint could not supply enough connection strength for high power engines. Interference assembly of knurled cam and tube has been widely used in camshaft manufacturing because of high connection strength, and no thermal deformation, etc [7, 8]. However, lacking of high machining reliability has been a problem in the assembled camshaft production for many years.

The studies on the assembled camshaft mainly focus on two aspects: the joining force and the connection strength. The joining force and connection strength of the assembled camshaft depend on many factors, including interference, geometric parameters, and material properties [9, 10]. For example, the assembled camshaft of 100Cr6 cam and AlMgSi tube was studied by Kleditzsch et al. [11, 12]. The results show that the tube chamfer angle has a crucial influence on the joining forces as well as the push out forces. Larger shaft chamfer
angles lead to lesser joining force. And a forming joining or cutting joining was realized depending on the shaft chamfer angle. Zhang et al. [13] investigated the relationship between independent camshaft assembly variables and the joining force. The optimal combinations of knurling tooth height, tooth angle, and feed are concluded for lesser joining force and larger connection strength. Stress between cam and shaft determine the operation of assembled camshaft, such as connection strength and fatigue. So, Sen et al. [14, 15] studied the stress distribution in relation to the ratio of contact length/diameter using the elastic/plastic FE model.

Generally speaking, the greater the interference, the greater the connection strength [16]. However, too much interference would cause bursting failure of the cam. The plastic instability is related to strain hardening exponent, plastic anisotropy parameter, and strength coefficient [17, 18]. In addition, process parameters, such as feed speed, are significant factors causing the initiation of failure [19, 20].

It is almost certain that the interference has an important influence on the connection strength. It determines the joining force and operation reliability of camshaft. However, for the camshaft with knurled tube and cam, the relationships between the interference and the joining force as well as connection strength are not analyzed fully. In this paper, the influence of interference on the joining force and connection strength is discussed by theory analysis. Then, the joining force and connection strength of five groups of camshaft with different interference are obtained by joining and torsion experiment. Metal plastic deformation, stress, and strain of knurled tube are analyzed systematically by metallographic observation and finite element method (FEM).

2 Mechanism of camshaft interference joining

Axial and radial section of the assembled camshaft is shown in Fig. 1. Axial rectangular convex-concave grooves are on the inside surface of the cam. The knurled teeth are on the external surface of the hollow tube in the direction perpendicular to axis. Concave/convex mosaic is generated by interference joining between tube and cam. The knurling interference connection are provided by both shearing and friction resistance.

2.1 Joining force and connection strength of camshaft

The joining force $F$ includes two parts: one is friction $F_f$ and the other is shearing force $F_s$.

$$F = F_f + F_s$$  \hspace{1cm} (1)

The friction force is as follows:

$$F_f = \mu P_j S_1$$  \hspace{1cm} (2)

where $\mu$ is the friction coefficient and $S_1$ is the interference as shown in Fig. 1. $P_j$ is the contact pressure between cam and tube. It changes with time and location in the joining process because of the three-dimensional structure of camshaft. The shearing process is a typical plastic forming process. It would be discussed in Section 2.3.

The connection strength $T$ is also composed of two parts, one is the friction torque $T_f$ caused by contact pressure, and the other is the shearing torque $T_s$ caused by knurled teeth of tube and grooves of cam according to Eqs. 3, 4, and 5.

$$T = T_f + T_s$$  \hspace{1cm} (3)

$$T_f = P_j S_1$$  \hspace{1cm} (4)

$$T_s = f(P, \tau, S_2)$$  \hspace{1cm} (5)

where $P$ is contact pressure between cam and tube after joining and $\tau$ is shear coefficient of cam. $S_2$ is determined by the distance $d$ between convex and concave grooves of cam as shown in Fig. 1.

2.2 Pressure and displacement of the cam and tube for elastic deformation

From the above analysis, we can see that contact pressure between tube and cam is the key factor affecting joining force and connection strength. $P$ is related to the interference and structure of camshaft.

To simplify the model, the thick-wall cylinder model is used to analyze the joining process [21]. According to mechanics assumption, the thick cylinder model is valid if $K_1=R_1/R_2\geq1.2$ and $K_2=R_2/\ell\leq10$, where $R_1$, $R_2$, $\ell$ are outside diameter, inside diameter, and thickness of the wall cylinder. The cam and tube are marked as thick wall cylinder 1 and 2, respectively. The inside and outside diameters of the cam are $R_{1i}$ and $R_{1o}$.

For cam: $K_1=35/24.65=1.4\geq1.2$, $K_{12}=35/5.2=6.7<10$.

For tube: $K_2=24.3/18.7=1.3\geq1.2$, $K_{22}=24.3/2.8=8.6<10$.

So, the thick wall cylinder model is available for them. During the joining process, the expansion pressure $P_{1i}$ acted on the inner surface of the cam. According to the solution of elastic mechanics, the stress and displacement of cam are presented in Eq. 6:

$$u(r) = \frac{1-\mu_1}{E_1}\frac{(R_{1i}^2 - R_{1o}^2)(P_{1i} - P_{1o})}{R_{1o}^2 - R_{1i}^2} + \frac{1+\mu_1}{E_1}\frac{R_{1o}^2 R_{1i}^2 (P_{1o} - P_{1i})}{(R_{1o}^2 - R_{1i}^2)^2}$$

$$\sigma_r (r) = \frac{R_{1i}^2 P_{1i} - R_{1o}^2 P_{1o}}{R_{1o}^2 - R_{1i}^2} - \frac{R_{1i}^2 P_{1i}^2}{(R_{1o}^2 - R_{1i}^2)^2}$$

$$\sigma_\theta (r) = \frac{R_{1i}^2 P_{1i} - R_{1o}^2 P_{1o}}{R_{1o}^2 - R_{1i}^2} + \frac{R_{1i}^2 P_{1o}^2}{(R_{1o}^2 - R_{1i}^2)^2}$$  \hspace{1cm} (6)
where \( \sigma_r(r) \) and \( \sigma_\theta(r) \) are radial stress and circumferential stress, respectively, \( u(r) \) is radial displacement, and \( E_1 \) and \( \mu_1 \) are the elastic modulus and Poisson’s ratio of the cam. When \( r=R_{1i} \), the stress and displacement are:

\[
\begin{align*}
\sigma_r(R_{1i}) &= \frac{1-\mu_1}{E_1} \frac{R_{1i}^2}{R_{1o}^2-R_{1i}^2} + \frac{1+\mu_1}{E_1} \frac{R_{1i}R_{1o}^2}{(R_{1o}^2-R_{1i}^2)} P_{1i} \\
\sigma_\theta(R_{1i}) &= \frac{1}{\mu_1} \frac{1+\mu_1}{E_1} \frac{R_{1i}}{R_{1o}^2-R_{1i}^2} P_{1i} \\
u(R_{1i}) &= -\frac{P_{1i}}{E_1 R_{1o}^2} \\
\end{align*}
\]

(7)

The stress and displacement of tube when \( r=R_{2o} \) is:

\[
\begin{align*}
\sigma_r(R_{2o}) &= -\frac{1-\mu_2}{E_2} \frac{R_{2o}^2}{R_{2o}^2-R_{2i}^2} + \frac{1+\mu_2}{E_2} \frac{R_{2o}^2}{(R_{2o}^2-R_{2i}^2)} P_{2o} \\
\sigma_\theta(R_{2o}) &= \frac{1}{\mu_2} \frac{1+\mu_2}{E_2} \frac{R_{2o}^2}{R_{2o}^2-R_{2i}^2} P_{2o} \\
u(R_{2o}) &= -\frac{P_{2o}}{E_2 R_{2o}^2} \\
\end{align*}
\]

(8)

The inside and outside diameters of the hollow tube are \( R_{2i} \) and \( R_{2o} \), respectively. The elastic modulus and Poisson’s ratio are \( E_2 \) and \( \mu_2 \). The outside diameter of the steel pipe is equal to the inside diameter of the cam after interference joining, \( R_{1i}=R_{2o} \). The radial pressure between cam and tube is \( P_{1i}=P_{2o}=P \), which is closely related to the stress state of the contact area.

The interference between the cam and the tube is as follows:

\[
\delta = u(R_{1i}) + u(R_{2o})
\]

(9)

### 2.3 Plastic deformation of the camshaft in the joining process

The plastic deformation, strain hardening, and failure criterion of the material are critical for the joining process. The plastic joining force \( F_s \) depends on the real contact area \( S_1 \), the contact pressure \( P \), and the coefficient \( X_{f,c} \) between tube and cam. It is described as in reference [11].

\[
F_s = f(S_1, P, X_{f,c}, \tau)
\]

(10)

The contact area \( S_1 \) between knurled tube and grooved cam is based on the knurled tooth profile and interference as shown in Fig. 1. The larger the interference, the larger the contact area \( S_1 \). The coefficient \( X_{f,c} \) varies depending on time and location during joining process.

At the same time, large plastic deformation can also lead to material hardening [22]. Strain rate, displacement rate, and stress rate affect the hardening coefficient of the material [23]. The shearing strain could be revealed as:

\[
\varepsilon = \left[ D_1 + D_2 \exp(D_3 \sigma^*) \right] \left[ 1 + D_4 \ln \varepsilon^* \right]
\]

(11)

where \( D_1, D_2, D_3, \) and \( D_4 \) are failure parameters of material and \( \sigma^* \) and \( \varepsilon^* \) are parameter of stress state and strain rate state.

For the joining process of camshaft, the stress and strain of each position are variable with time. It is very difficult to get the joining force and connection strength using theoretical model for real camshaft because of the three-dimensional coupling interaction of elastic and plastic deformation. However, the above analysis provides theoretical support for the subsequent experimental results and FEM results.

### 3 Experiment and FEM model

#### 3.1 Experiment set up

Joining process is performed on SHT4304 electro-hydraulic machine. Static torque capacity is obtained by static torsion
system (SLPCL). Joining speed and rotation speed are set as 40mm/min and 10°/min at room temperature. In the joining process, a series of cams are fitted onto the tube in order in actual assembled camshaft, in which each cam is independent. One cam is paired with one tube during the experiment in order to facilitate the experiment and measurement.

The geometric parameters of the cam and tube are shown in Fig. 1 and Table 1. The number of knurled teeth on the tube is nine. The values in Table 1 are empirical parameters used in industry manufacturing production. And they are taken as reference geometric parameter.

The interference between the cam and the shaft is defined as $\delta = (R_{1o} - R_{2i})/2$. Different interference is controlled through different inside diameter of cam $R_{2i}$. $R_{2i} = 24.2$ mm, 24.1 mm, 24.0 mm, 23.9 mm, 23.8 mm, and 23.7 mm, respectively. There are six groups of different interference assembled camshaft. The interference is as follows: $\delta = 0.05$ mm, 0.1 mm, 0.15 mm, 0.2 mm, 0.25 mm, and 0.3 mm, respectively. Each group has four cams for joining, in which the interference between cam and tube is constant to ensure the experiment reliability. In our experiment case, 24 samples are tested in total. The cam material is GGr15, and the tube material is E355.

After joining, the camshaft is cut in axial and radial direction by A1100S wire-electrode cutting machine. The micro details of the knurled tube are analyzed using metallographic microscope.

### 3.2 FEM modeling

The joining process is studied by using the FEM software ABAQUS. The basic mechanical property parameters of the shaft and cam are listed in Table 2 [9]. The cam is defined as rigid in the FEM model because the hardness ratio between GCr15 and E355 approximately is 3/1. Cam has a hardness of HRC 64.2, which is much higher than that of tube. In the FE model, the stress/strain curve of E355 is used, which is obtained using the tensile experiment values as shown in Fig. 2.

Only quarter of one tube knurled teeth is modeled due to the rotational symmetry. A coupled Euler-Lagrange analysis is applied in the model which is suitable for large deformation. The cam is set as fixing constraint. The axial displacement is applied to the tube to simulate the joining process. The displacement velocity is set as the same as the experiment 40mm/min. The Coulomb friction model is adopted in the FEM simulation. Friction coefficient of joining without lubrication is 0.125 [24, 25]. The contact area between the cam and the tube is the focus of study. The mesh in this area is refined to obtain more accurate results. C3D8R mesh is introduced to discrete the FEM model. The total number of elements and nodes for the model are 14040 and 25935.

### 4 Results and discussion

#### 4.1 Effect of interference on joining force and connection strength

Joining force and connection strength are determined by both elastic and plastic deformation of knurled tube material. Detailed information about joining force and connection strength under different interference between tube and cam material is shown in Table 1 and Fig. 2.

**Table 1** Geometric parameter of tube and cam

| Tube | Cam | Interference $\delta$ |
|------|-----|-----------------------|
| $R_{1i}$ | $R_{1o}$ | Knurling teeth |
| $R_{2i}$ | $R_{2o}$ | Grooving parameter |
| $h$ | $r$ | $P$ |
| $d$ | $H$ |
| 18.7 | 24.3 | 0.65 | 0.16 | 1.57 |
| 23.9 | 39.0 | 1.02 | 0.35 | 0.25 |

**Table 2** Basic mechanical properties of E355 and GCr15 materials

| Material | Yield strength (MPa) | Modulus of elasticity (GPa) | $\mu$ | HRC |
|----------|----------------------|----------------------------|-------|-----|
| E355     | 530                  | 198                        | 0.3   | 21.3 |
| GCr15    | 632                  | 206                        | 0.28  | 64.2 |

Fig. 2 Engineering load/displacement curve
are listed in Table 3. When interference between cam and tube is 0.3 mm, the cam will crack, and no valid joining force is obtained. This means that the cam would be at risk of fracture when the interference exceeds a certain limit. It will be discussed in the future research.

Joining forces of 12# experiment are plotted in Fig. 3 when the interference is 0.15 mm. Joining forces fluctuating increase are observed in the process of joining. The joining force decreases when one knurled tooth is pushed down completely. And it increases when the next knurled tooth is pushed in. Fluctuating joining forces is because of the knurling gap between two neighboring knurled teeth. The joining force gradually increases up to 14.07 KN.

As explicated in Section 2, the joining force is composed of friction force and shearing force. It increases with the joining length. The polynomial interpolation can be used to describe the increasing law:

$$F(l) = \sum_{i=1}^{9} F_{f,i}(l) + F_{s,i}(l)$$  (12)

where $l$ is the joining length and $i$ is the knurled tooth number of joining. There are 9 knurled teeth in total on the tube for each cam. For example, \(\sum_{i=1}^{9} F_{f,i}(l)\) stand for the friction force of the ninth knurled teeth, and \(F_{s,9}(l)\) stand for the shearing force of the ninth knurled tooth in the joining process and so on.

Firstly, the difference of joining force between the first tooth and the last tooth is calculated. It is eight times of the friction force of single knurled tooth joining. So the $F_s$ and $F_f$ can be obtained using both Eq. 12 and joining force experiment data. For interference 0.15mm, \(F_s\) is 0.87 KN, and \(F_f\) is 6.23 KN. Ignoring the influence of experiment error, the joining force can be simplified as linear increase with the increase of joining length (as shown in the oblique dotted line in Fig. 3). The rising rate is about 0.55KN/mm during joining process.

The experimental curves of static torsion strength are shown in Fig. 4 when the interference is 0.15mm. The curves could be divided into three stages: linear rising (elastic), non-linear rising (plastic), and decline (failure).

The torsion speed is set as 10°/min. The corresponding torsion angles of plastic deformation and failure are 1.15° and 8°, respectively. The cam begins to slip and lose efficacy when the torsion angle is greater than 8°. The maximum torsion is

| $\delta$ (mm) | No. | $R_{2i}$ (mm) | $F$ (KN) | $T$ (Nm) |
|--------------|-----|--------------|----------|----------|
| 0.05         | 1#  | 24.21        | 8.24     | 358      |
|              | 2#  | 24.23        | 7.46     | 357      |
|              | 3#  | 24.21        | 7.83     | 384      |
|              | 4#  | 24.19        | 9.27     | 421      |
| 0.1          | 5#  | 24.12        | 11.93    | 522      |
|              | 6#  | 24.11        | 12.08    | 543      |
|              | 7#  | 24.11        | 12.43    | 602      |
|              | 8#  | 24.13        | 11.96    | 581      |
| 0.15         | 9#  | 24.03        | 13.25    | 566      |
|              | 10# | 24.01        | 13.92    | 593      |
|              | 11# | 24.02        | 13.96    | 637      |
|              | 12# | **23.98**    | **14.07**| **654**  |
| 0.2          | 13# | 23.80        | 16.92    | 711      |
|              | 14# | 23.81        | 16.84    | 678      |
|              | 15# | 23.83        | 16.73    | 664      |
|              | 16# | 23.80        | 17.45    | 623      |
| 0.25         | 17# | 23.69        | 21.17    | 675      |
|              | 18# | 23.67        | 21.33    | 726      |
|              | 19# | 23.71        | 20.54    | 659      |
|              | 20# | 23.71        | 20.93    | 696      |

![Fig. 3 Joining force curve of 12# experiment](image_url)
654.2 Nm, which is much higher than the requirement of typical static torsion 200 Nm [26]. The maximum torque is the connection strength of assembled camshaft.

Larger interference leads to higher joining force and higher connection strength as shown in Table 3. Joining force should be kept as low as possible for assembly accuracy. And greater torsion is desired for reliable connection. However, joining force and torsion increase with the increase of interference as we can assume.

When the interference is 0.05 mm, 0.1 mm, 0.15 mm, 0.2 mm, and 0.25 mm, the average maximum joining force is about 8.2 KN, 12.1 KN, 13.8 KN, 17.0 KN, and 21.0 KN, respectively. The corresponding torque is 380 Nm, 562 Nm, 613 Nm, 669 Nm, and 689 Nm, respectively. The average joining force and connection strength for different interference group are shown as histogram in Fig. 5. The torque has a significant increase when the interference increases from 0.05 to 0.1 mm. However, the torque increased slowly when the interference increases from 0.1 to 0.25 mm.

The relationship between interference and joining force and torque can be expressed by fitting as:

\[
T = \frac{858.7 - 434.1}{(1 + 400\delta)^{0.696}},
\]

\[
F = 61.2\delta + 5.26
\]  

(13)

For interference 0.25 mm, the relative growth rate of connection strength is \((T_{0.25} - T_{0.05})/T_{0.05} = 81.3\%\), and the relative growth rate of joining force is \((F_{0.25} - F_{0.05})/F_{0.05} = 156.1\%\), which is calculated based on interference 0.05 mm
group. The relative growth rate of connection strength is lower than that of joining force when the interference increased. This means increasing interference unilaterally is not a good way to improve the connection strength.

4.2 Metal plastic deformation of knurled shaft

Fig. 3 shows the morphology of 12# camshaft after joining. The knurled teeth are pushed down to the cam inner surface. The tube is embedded into the groove structure of the cam. The knurled teeth are squeezed severely as the experiment and FEM results shown in Fig. 6a and b. The contact between the tube and the cam is discontinuous because of the inside splined profile of the cam. This kind of connection can provide additional connection strength under the condition of twist.

Fig. 6c revealed that the geometric configuration of the cam remain unchanged after joining. This result proved that the rigidity assumption of cam is feasible in the FEM model. The cam fails due to cracks as show in Fig. 6d when the interference increases to 0.3 mm. Therefore, large interference between cam and tube should be avoided.

Metal flow lines of the knurled teeth along axial direction and the radial direction are shown in Fig. 7. From radial section of the camshaft in Fig. 7b, we can see that the materials of the knurled tube are pushed into the valley of the cam. Concave and convex mosaic are formed by plastic flow of the tube material into the interspaces of the cam. Knurled teeth of the tube can be divided into three zones according to metal deformation characteristics as shown in the axial section of Fig. 7c.

Zone I is elastic deformation zone. Metal streamline of this zone is almost parallel to the axis direction without plastic deformation. This is supported by FEM results in Fig. 8. Zone II is plastic squeeze zone. The knurled tooth is com-
pressed tightly to the inside surface of the cam. It is extruded in the axis direction as shown in Fig. 7b and 7c. Zone III is the plastic bending zone. The material in Zone III tends to flow towards the free valley between neighboring teeth of tube. Triangular knurled teeth gradually turn over under the extrusion action of cam. The top of knurled tooth gradually formed an inverted triangle shape finally as shown in Fig. 7d.

4.3 Stress and strain

The stress, displacement, and plastic strain nephogram after joining are shown in Fig. 8. As represented in Fig. 8a, the highest compressive Mises stress 587 MPa is observed on the top portion of the tooth. It exceeds the yield limit of tube material, indicating that plastic deformation occurs in some areas. Residual stress is over 300 MPa for most regions of the knurled teeth.

The maximum plastic strain regions are located in the central part of the knurled tooth. The maximum equivalent plastic strain (PEEQ) reached 6.49. This means that material yield and hardened severely in the top half of the knurled teeth. No obvious plastic strain is observed under the depth of 0.5 mm from the top of the tooth.

The maximum displacement in Y direction is 0.458mm, which corresponds to tooth material sliding displacement in axial direction. And the maximum displacement of 0.156mm in Z direction corresponds to interference extrusion in radial direction. This is consistent with the interference value of 12# experiment.

5 Conclusion

In this investigation, the aim is to analyze the joining force and torque of camshaft. The camshafts are interference assembled by knurled cam and tube. The experiment is carried out, in which the cam is made of E355 and the tube is made of GCr15.

(1) Joining force and connection are determined by the combined action of friction and shearing. In order to obtain the influence of interference on the joining force and connection strength, formulas of joining force and connection strength are discussed using the thick wall cylinder model and elastic/plastic mechanics.

(2) There is a positive correlation between the interference and joining force and connection strength. Joining force fluctuating increases with joining length. It is caused by the knurled teeth of cam and tube. The relationship between the joining force, torque, and the interference of the camshaft is established by linear fitting and exponential fitting. The relative growth rate of connection strength is lower than that of joining force.

(3) Experiment and FEM results reveal that cross connection is formed between tube and cam. There are elastic deformation, plastic deformation, and plastic bending deformation in the assembled tube. Metal streamlines show that triangular knurled teeth turn over and formed an inverted triangle shape. Residual stress 587 MPa is observed on the top portion of the tooth, and the maximum PEEQ reached 6.49 after joining.

(4) In order to avoid expansion crack of the cam, the interference cannot be greater than a certain value 0.3 mm for the given case in this paper. Further studies for assembly interference limitation and crack mechanism of cam are needed. And the limitation of this study is that the influence of knurling process on hardening of knurled tooth is ignored in FEM.

Author contribution The author contributions are as follows: Xiaoming Huang was in charge of the whole trial and designed the study; Xiaoming Huang and Wentao You wrote and edited the manuscript; Weitao Sun and Yuqian Wang assisted with sampling and laboratory analyses; Xiaoliang Liu and Yucan Wang provided guidance and discussion in theory; Jin Xing and Hailin Bi performed the experiments. All authors read and approved the final manuscript.
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**Declarations**

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**Consent to participate** Not applicable.

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